NASA CR-72179
TD-5699

A POWER CONDITIONER
FOR
EXPERIMENTAL MODEL
SERT II ION THRUSTOR

by

P. D. Corey

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS3-7939

GENERAL ELECTRIC COMPANY
SPECIALTY CONTROL DEPARTMENT
WAYNESBORO, VIRGINIA

Requests for copies of this report should be referred to

National Aeronautics and Space Administration
Office of Scientific and Technical Information
Attention: AFSS-A
Washington, D. C. 20546

CONTENTS

NASA CR-72179
TD-5699

A FINAL REPORT POWER CONDITIONER FOR EXPERIMENTAL MODEL SERT II ION THRUSTOR

by

P. D. Corey

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

May 17, 1967

CONTRACT NAS3-7939

Technical Management
NASA Lewis Research Center
Cleveland, Ohio
SPACECRAFT TECHNOLOGY DIVISION
William P. Blake

GENERAL ELECTRIC COMPANY
SPECIALTY CONTROL DEPARTMENT
WAYNESBORO, VIRGINIA

SUMMARY

This contract successfully developed circuits and Ion thrustor ground-test hardware for efficient, reliable, potentially lightweight power conditioning. A single breadboard, two rack-mounted models, and a dummy load were built and delivered, Tests were run at Lewis Research Center with a mercury ion thrustor. After a 50-hour endurance run one engine and power conditioner were committed to a life-testing program. This power conditioning system is suitable for flight packaging and mission application.

INTRODUCTION

Prior to the work done here, several single-output ion thrustor supplies were constructed (refs. 1 and 2), and some earlier programs resulted in development of intermittent-duty multiple output ion thrustor supplies (refs. 3, 4 and 5). Continuing studies (refs. 6 and 7) have shown the desirability of realizing a true long-endurance electric propulsion capability. The overall purpose of the work of this contract was to develop the power conditioner equipment incorporating all of the multiple-output closed-loop control features required together with the necessary efficiency and reliability for practical long-term space missions.

During performance of this contract, special reports were issued covering new technology. These reports dealt with true RMS regulation and a novel magnetically coupled multivibrator circuit.

Performance of this contract involved design of the power conditioner circuitry and construction of a breadboard for testing with the actual ion thrustor at NASA-LeRC. Upon completion of these tests and a design review, the two production power conditioners were built and tested.

During this development program alterations in thrustor requirements (such as elimination of the electromagnet, an entirely new neutralizer arrangment and changed vaporizer control) required redesigning. The resulting final equipment features a very high degree of flexibility which should prove quite useful during future development test programs. The modular configuration of the final packaged power conditioners facilitates 'both small and relatively major changes.

Near the end of this program one production power conditioner was shipped, together with a NASA-LeRC thrustor, to an external laboratory facility for a life test. The remaining production power conditioner and the breadboard equipment were retained at NASA-LeRC for use in thrustor development tests.

In May 1967 the life test power conditioning operated unattended for 549 consecutive hours. At 549 hours the ion thrustor failed. The power conditioning automatically shut down safely. NASA life test console shown in Figure 61 and 62.

This power conditioning system has accumulated more than 820 hours operating time. No thrustor life test has been terminated by failure of this power conditioning.

Operation of all three power conditioners has been completely successful. The close coordination with NASA on electrical requirements of the thrustor was a major contributing factor to the degree of success attained.

Costs of this contract were shared 60%/40% NASA/GE.

DESCRIPTION OF THRUSTOR OPERATION

The thrustor system consists of three subsystems.

A. Propellant feed

The propellant feed subsystem consists of a storage reservoir, vaporizer, and vaporizer heater. Gravity forces the liquid mercury (Hg) propellant against the vaporizer. The vaporizer is a permeable metal plug heated by electrical power. It allows hot Hg vapor to flow through it. Vaporizer heater input power controls the mass flow rate of the Hg vapor to the thrustor.

B. Thrustor

The thrustor subsystem consists of an anode, cathode, magnetic field, HV+ electrode, and HV- electrode. Shown in Figure 60. The Hg vapor supplied to the cylindrical anode region undergoes bombardment by electrons and is ionized. This region is the arc chamber. The energetic electrons are obtained by the thermionic emission from a cathode heated by electrical power. The electrons are accelerated to anode potential. A magnetic field surrounds the arc chamber. This field increases the length of the path of the electron with the arc chamber. This enhances ionization of Hg.

The Hg ions reaching the region of the HV+ electrode (screen) are focused and accelerated by the HV electrostatic field associated with the perforated HV+ (screen) and HV- (accelerator) electrodes. Effective thrust is obtained by neutralizing the ion beam with electrons.

C. Neutralizer

The neutralizer provides the electrons necessary to maintain a zero net charge in the expelled ion beam. The neutralizer operates near spacecraft potential. There are two types of neutralizers.

The simplest form of neutralizer is a hot oxide coated cathode. This cathode is heated by one power supply and emits electrons to the ion beam. It is a fragile device and has a lifetime too short for 500 hour tests.

The plasma bridge neutralizer is rugged enough for 1000-5000 hour duration tests. A small propellant feed system similar to the arc chamber propellant feed supplies liquid Hg to the vaporizer. Electrical power heats the vaporizer for controlling the Hg vapor to the neutralizer cathode. The neutralizer cathode is a thermionic electron emitter heated by electrical power. The ionized Hg vapor flowing from the neutralizer serves as a plasma bridge for coupling the neutralizer omission current (electrons) to the ion plasma beam exhaust from the thrustor. The neutralizer emission current is controlled by sampling the plasma bridge potential with the neutralizer anode and using this potential for feedback control of the neutralizer vaporizer.

DESIGN

Evolution of Electrical Requirements

This project necessarily involved very close coordination with the thrustor developments concurrently in progress at NASA-LeRC. As the requirements for the thrustor evolved, so did the electrical requirements imposed on the power conditioner. Figure 1B shows a sketch of the thrustor as originally planned compared to the final configuration. Shown in Figure 1A.

A key to the success of this project is the inherent flexibility of the design of the power conditioner. The attainment of the final design necessitated various redirections during the course of the project. Completely successful automatic startup and operation of the final NASA-LeRC thrustor was demonstrated with the final breadboard power conditioner within one year from date of contract, The first production unit was delivered within 7 weeks after these tests.

Following is a discussion of a more specific nature outlining the evolution of the actual electrical requirements for this power conditioning equipment.

1. Power Source

The power conditioners were designed to be supplied from a solar cell array source having the characteristic shown in Figure 2. This required that the power conditioner be capable of continuous operation over the range of 40 to 60 VDC with any combination of loads. Design is such that if the input exceeds 60 VDC, operation is automatically discontinued. Automatic recycle and start occurs when the input voltage returns to 60 VDC and below. During intervals when the input falls below 40 VDC, power conditioner outputs do not exceed any rated values and there is no damage. An additional vaporizer control requirement was later added, specifying that in the 41-40 VDC range (near the end of useful solar cell life) the vaporizer supply (V2) be proportionally backed off, gradually reducing mercury flow and extending the mission life at reduced thrust levels.

2. Magnetic Field Supply (V1)

A 4 VDC 15 ampere supply for the thrustor magnetic field was originally specified, and a 4V/3V tapped output was later desired. Later the V1 supply was completely discarded, since the newer thrustor utilizes permanent magnets.

3. Feed (Thrustor Vaporizer) Supply (V2)

The thrustor vaporizer is an AC heater operating in the range of 6 VAC (3V tap) and 3 amps (6A tap) with 2% line and 2% load regulation requirements. This supply floats at the nominal +3KVDC Screen Supply (V5) level. These requirements were not altered during this program.

Control requirements of the V2 supply were changed, however. Originally, V2 was voltage regulated with accelerator current override. After verification tests at NASA-LeRC, accelerator impingement override control was discarded in favor of Screen (V5) current override control. This change resulted in regulating the thrustor beam current by controlling the mercury feed instead of cathode emission.

3. Feed (Thrustor Vaporizer) Supply (V2) (cont'd)

Another control change came about with the realization that the feed heater experienced a 2:1 (typical) increase in resistance during initial warm-up with a relatively long (30 sec.) time constant. In order to cope with the overload condition which could result from this load impedance change, a change in V2 control from voltage to current limit was recommended and accepted. The specification was appropriately modified.

4. Thrustor Cathode Supply (V3)

The cathode is a Barium-activated tungsten mesh which is rated for a maximum 4 VAC 50A RMS $\pm$ 5%. Normal operation is 125 watts steady state. This principal electrical rating was unchanged during this program, with the important exception that the thermal effect on resistance was not documented quantitatively at the outset. This resistance increase during warm-up was later recognized to be a 6:1 effect, and this wide load range influenced the selection of the design approach and RMS regulating scheme.

Control requirements of the V3 supply were changed during initial tests with the NASA-LeRC development thrustor. Originally the cathode supply was controlled from (1) the anode current (I4), (2) the Screen current (I5), and (3) low power conditioner input voltage (40-41 VDC proportional cutoff). The latter two requirements were eventually deleted in favor of simple anode current control. The anode current level is selectable from one of three steps by a switch (or ultimately a command relay). When anode current is low, the cathode current is limited to an adjustable RMS maximum. This RMS limit is true regardless of current waveform.

A separate external V3 transformer was ultimately specified and supplied to reduce lead losses.

5. Thrustor Anode Supply (V4)

The thrustor anode is a DC load which imposes a maximum rated load of 36 VDC at 7A. Similar to the V1, V2, and V3 supplies, V4 is at +3KVDC relative to ground. Peak ripple = 10% max.

Originally, the anode supply was closely regulated (2% line, 2% load). However, as the project progressed the regulation requirement was relaxed to 4% line, 4% load, and finally to permit 10% load regulation with the line regulation requirement deleted completely. This drastic alteration of specified regulation requirements finally enabled the elimination of a separate V4 inverter, the anode output being obtained directly from the main power inverter, which is unregulated.

Corresponding simplifications evolved in the control of the V4 supply. The initial requirement to reduce V4 proportionately to 0 volts in accordance with a preset cathode current drop was dropped with the advent of beam control of V2. Anode voltage adjustment was changed from a continuous potentiometer setting to an arrangement of transformer tap selection for the ranges of 20, 25, 30 or 36 VDC.

5. Thrustor Anode Supply (V4) (cont'd)

During the course of engine tests at NASA-LeRC it was determined that an elevated V4 potential is necessary in order to initiate the thrustor anode-cathode discharge when starting. Accordingly, the requirement to provide a minimum of 100 VDC at I4 less than 10 ma was added. The power conditioner design was altered accordingly to achieve this performance.

6. Screen Supply (V5)

This requirement is for 3 KVDC at 0.25A. The negative side of this supply is grounded. The only change in requirements for this supply was opening up the load regulation tolerance from 5% to 10%. V5 is not regulated, and is a direct function of the power conditioner supply voltage.

The Screen current (I5) was originally controlled by closing the loop through the cathode supply, V3. As the development program advanced, the change (previously discussed) to control I5 by thrustor vaporizer (V2) was implemented. Operation was smooth and completely successful during thrustor tests.

7. Accelerator Supply (V6)

The accelerator electrode normally requires only about 1 - 3 ma DC at 2 KVDC potential, with the positive terminal of this supply grounded. However, during normal operation, surge overloads of several seconds duration can occur, requiring that this supply be rated at 50 ma DC continuous. Since arcs occur between V5 and V6, it is necessary that the accelerator be capable of the same surges as the screen supply. This requirement sized the HV rectifiers and closely-associated circuitry.

The only change in electrical rating was increasing the regulation tolerance from 5% to 10% with load. Like the V4 and V5 supplies, V6 is not voltage regulated, but provides an output which is proportional to the power conditioner supply voltage.

The accelerator impingement was originally limited by closing a current-limit loop through the Feed supply, V2. The control loop rearrangement now used controls V2 as a selectable function of I5 (Screen current). It removes the I6 control circuit, protecting against excessive continuous values or I6 with the integrating trip circuit.

8. Neutralizer Supplies (V7, V8, V9)

The initial requirement was for an RMS-regulated 3 VAC, 15A supply for a thermionic neutralizer. Provision was made for automatic transfer of this power to an alternate redundant neutralizer in the event of an open-circuited primary neutralizer or upon ground command. This supply was to be at ground potential.

Later thrustor development at NASA-LeRC resulted in the adoption of a novel, long life neutralizer which required 3 entirely new and different outputs as follows:

a. A neutralizer cathode (V7) was required, rated at 6 VAC, 7A with a 6:1 resistance change from cold start to nominal running. 5% line and 5% load true RMS current regulation was specified.

b. A neutralizer vaporizer (V8) was requfred, rated at 3.2 VAC, 3.2A with a 3:1 resistance change from cold start to normal running. 2% line and 2% load true RMS current regulation was required here.

c. A neutralizer anode (V9) was also required. This supply was initially rated at 55 volts DC at light load with 55 ma DC output at short circuit. There was no line regulation requirement; however, the output impedance was to look like a straight line resistance. Later on, it was found that the neutralizer plasma bridge discharge would not start reliably unless the no load voltage of V9 was 190 VDC (similar to the V4 situation). This change was made to the final equipment before delivery. The neutralizer probe potential was sensed and a control loop closed through V8 so that the mercury feed to the neutralizer system could be maintained at the level which was exactly adequate to regulate the main thrustor beam at any selected value. A continuous adjustment provides this setting, 0 to 50 VDC. Nominal operation occurs at 15 volts.

d. The desirability of a neutralizer bias was investigated during final thrustor tests, but no definite steps were taken to define this requirement with regards to this specific program. The SERT II equipment will contain a reversible step-adjustable supply for investigating this possibility further, however. The present equipment does make provision for connection of such a bias supply by bringing out the neutralizer ground separately, rather than connecting the neutralizer supplies directly to ground.

POWER CONDITIONER CIRCUIT DESCRIPTION

This section discusses the operation of each portion of the power conditioner circuit. To facilitate reference, each subcircuit is included in this section as a separate figure. (For general reference purposes, Appendix B is included which consists of the actual complete schematic diagram for the entire power conditioner as finally delivered.)

1. V2 - Thrustor Vaporizer Supply (Feed)

Referring to figure 2 it is seen that the feed supply operates on the series dissipative regulator principle, with Q63 (2N1016D) acting as the controlled resistive element. The diodes CR163 and CR164 are connected to collectors of power switching transistors in the SAAF (Screen/Accelerator/Anode/Feed) inverter, thereby impressing a square wave voltage on the primary of the V2 output transformer, T16, with amplitude determined by the Darlington pair Q63/Q64.

Control of V2 is exercised in four ways: current-limit, screen current, low input voltage, and the feed clamp, the feed clamp shuts V2 off for about 1 second during arcing/recycling.

Current limit is obtained by sensing I2 via current transformer CT26 and by exercising closed loop control back to the series dissipating transistor via Q83, Q66/Q3, and Q64. Zener diode CR299 (1N3016B, 6.8V) provides the required reference for comparison and control. Feed current regulation as the result of load variations (open circuit through short circuit) is shown on figure 3. Figure 4 illustrates I2 variations with variation of the DC power source. Performance is well inside specified limits.

Screen current (I5) control of feed (I2) is obtained by sensing I5 via current transformer CT21 and comparing the DC voltage obtained (after rectification and filtering) with the same reference, CR299. CR349 is present to clip surges induced by screen circuit arcing. The I5 signal applied through CR172 overrides the current-regulator control (CR173) and results in closed-loop dynamic control of the ion thrustor beam current (I5) at the value selected by control range selector, S15. Performance of this control mode is shown on Figure 5, with requirements again easily met.

Low input voltage V2 cutoff control is exercised through Q80 and associated circuitry. The -23 VDC bias supply bus provides the reference with R470 used to set the control range (typically 40-41 VDC). The output of this circuit is "or'ed" in via CR199. Figure 6 shows the action of this feature which controls over a 1.0 volt input voltage band.

During recycling of the power conditioner resulting from arcing, etc., the V2 supply is clamped to zero for 1 second to avoid pouring excess mercury into the engine. A series of arcs will reduce propellant flow until conditions improve and normal operation returns. The feed clamp signal is applied through CR197. This signal is produced by the control logic section, as will be described later. Figure 7 shows an oscilloscope trace illustrating the action of the feed clamp.

Both V2 and I2 telemetry signals are required. V2 telemetry is produced by rectifying the output of T16, winding 4-5-6. I2 telemetry is obtained by a separate current transformer CT8 and associated circuitry. In common with the other telemetry circuits, V2/I2 telemetry circuits may be shorted **or** open-circuited with absolutely no influence on the operation of the power conditioner. Figures 8 and 9 show the characteristics of the V2 and I2 telemetry, respectively.

2. V3 - Thrustor Cathode Supply

The main thrustor cathode is supplied with a quasi-square wave AC produced by the transistor bridge inverter shown on Figure 10. The output transformer of this inverter (T17) is mounted remotely near the ion thrustor in a separate subassembly to minimize the large line drop resulting from the 50 amp 4 VAC cathode requirement. The cathode inverter is driven by the SAAF driver. The action of DC control windings on reactor L5 determines the relative phasing of the switching of Q69/Q70 vs. Q67/Q68, thereby controlling the inverter output voltage. Thermistor TH-3 provides an output indicating the case temperature of the power switching transistor, Q70.

Cathode current and voltage telemetry signals are obtained by CT6 and a winding on the output transformer T17. Figures 11 and 12 show the transfer characteristics for V3 and 13.

Cathode inverter control is exercised in the form of self current-limit control and anode current (I4) control of cathode (I3). Figure 13 shows the circuits used to produce each of these forms of control.

Self current-limit control was specified to hold within a 5% band of the RMS current set point. This specification demanded the development of a true RMS current sensor which would be accurate and stable with life and temperature. Referring to Figure 13, I3 is sensed by CT27 and the resulting output is converted to a DC signal (voltage proportional to 13). This signal is then applied to a non-linear diode-resistor square-law approximation network. The result is that the collector current of Q71 follows the instantaneous square of the cathode current I3. This collector current is averaged (C62/R283) and compared to a reference (CR246) to give the desired RMS regulating action by regulating mean square current. Q72 (2N2905A) is the error amplifier. It controls the current in the phase displacement reactor (L5) control winding.

The circuit which produces the anode current (I4) control of cathode current (I3) is also shown on Figure 13. Here, CT24 is used to sense I4 and to generate a DC signal at the base of Q76 proportional to the average value of I4. bitter follower Q76 produces an impedance transformation. The resulting 14-proportional voltage is compared to a DC reference (CR248) through another control winding on the control reactor, L5. As I4 increases above the selected threshold (set by S16/S17), L5 control current is increased in the direction resulting in less output from the cathode inverter. This gives the desired control.

Figure 14 shows the performance of the cathode current regulator and Figure 15 illustrates the control of I3 exercised by variations in the anode current, I4.

During the development of the V3 supply it was learned that the load current, although feeding a nominally resistive load actually looked quite inductive. Pumpback diodes (CR230, CR233, CR231, CR234, Figure 10) compensate for this,. A centertap inverter can supply an inductive load if mil-square output is all that is desired. However, a centertap inverter is incapable of producing the type of constrained quasi-square wave desired here. This rules out the centertap connection for the V3 supply. Thus a bridge inverter was used.

3. V4 - Thrustor Anode Supply

The thrustor anode is energized via the main inverter. This inverter is of centertap design, and uses 8 - 25 ampere, 200 volt silicon transistors in push-pull parallel connection. Two centertap circuits are operated in exact synchronism. The output transformer secondaries are seriesed to insure exact load division between the two halves of the inverter. (Figure 16).

The current transformer CT25 produces a trip signal to the control logic which, in turn, cycles the driver switch Q91 until the cause of the current overload has been corrected, or the power conditioner is commanded "off" by either external or internal means. T27 and associated magnetically-coupled multivibrator components constitute the main inverter driver.

The SAAF (Screen/Anode/Accelerator/Feed) inverter was significantly altered during the course of the project. These alterations improved efficiency and substituted the new V4 supply (anode) for the deleted V1 (magnetic field) supply. SAAF power transistors are driven in an improved manner; T27 produces a very fast-rise square wave drive source. Speed-up capacitors (C96 through C103) act to remove stored charge quickly to minimize storage delay during switch-off. The separate driver uses the efficient, fast switching DTS-423's.

Anode voltage is adjusted by taps on the output transformer primaries (T25, T26). These taps are selected by toggle switches (S13, 14). Flight hardware could include tap-changing relays, if V4 adjustment still proved desirable.

We experienced two failures during preliminary testing. The anode circuit now uses Unitrode Avalanche rectifiers throughout. The output filter capacitor is protected by a 50-watt zener connected directly across the anode supply output terminals with short leads. Outrigger windings on the anode output transformers provide the 100+ volts at no load. This added feature starts the ionization chamber discharge.

Overcurrent protection (for the anode only) is provided by obtaining an overload signal from the I4 telemetry (voltage drop across R211). Instantaneous overcurrent protection is obtained by sensing total SAAF collector current (CT25) which can trip the inverter control binary in the logic/control circuit, shutting off SAAF drive and initiating automatic recycling.

Figure 17 shows the regulation characteristics of the V4 supply for the various combinations of selector switch positions. Figures 18 and 19 show the transfer characteristics of V4 and I4 telemetry outputs.

Anode voltage ripple at full rated 7 amp load is shown on Figure 20. Filtering of the anode supply was found to be necessary. Instantaneous fluctuations in anode potential are reflected in the beam current waveform. A pulsating beam current causes poor ion thrustor performance.

4. V5 - Thrustor Screen Supply

The main power output from the power conditioner is in the form of the 3 KV screen supply. This supply is vital in that it is primarily responsible for the ion engine's thrust output. This output is proportional to the screen current times the square root of screen voltage.

Arcing from screen to accelerator possibly including other electrodes normally occurs within the thrustor. Arcing is frequent during the initial running break-in phase of operation. This situation requires that the HV rectifiers be capable of withstanding high current surges and severe transient voltages without degradation. The filter components must be able to withstand direct short-circuiting and not generate damaging current surges.

Referring to the schematic (Figure 21) the rectifiers are shown as CR185 through CR196. These are unitrode USR20 2 KV avalanche fast reverse recovery devices which are rated to withstand 100 amp surges. Since these devices are designed for avalanche operation, no transient or steady state voltage-sharing components are needed for series-string operation. It is significant that, in spite of much abuse and severe service during breadboard testing, there were no HV rectifier failures. There is no evidence of any degradation of these devices.

To limit arc surges to reasonable levels, the series resistor string (R249) is connected in series with the filter capacitor, C50. This series resistance limits I5 surges to approximately 3 times the rated .25A DC screen current. Not only does this current-limiting action tend to protect components such as C50 from screen current pulses, but the energy delivered to the arc in the thrustor is also limited in instantaneous peak amplitude. Future thrustor tests may show that limiting the arc energy speeds the recovery time of the arc such that power conditioner recycle time may be significantly reduced. Faster recovery from arcing would maximize the integrated thrustor impulse over a given time interval.

Screen supply regulation with load was found to be strongly influenced by the leakage reactances of the output transformers (T9, T10). The breadboard equipment output transformers resulted in the regulation curve (V5 versus I5) shown in Figure 22. The production conditioners had transformers with additional insulation and resulting increased interwinding spacing resulting in increased leakage reactances. This effect is evidenced by the noticeable regulation increase illustrated on Figure 23, Future designs should concentrate on attempting to reduce transformer reactances, while maintaining an adequate safety margin of insulation. This aspect of HV inverter design could profitably be the subject for future development programs.

The required V5/I5 telemetry signals are obtained via separate windings on T9-T10 and by the separate telemetry current transformer CT13. Figures 24 and 25 show the transformer characteristics of these T/M outputs.

5. Bias Inverter - DC Supply Telemetry

The schematic diagram, Figure 21, shows the low power Bias Inverter. A pair of 2N2911 transistors operate in a magnetically-coupled multivibrator circuit. They supply a 2 KHz square wave to bias and T/M circuits requiring an uninterrupted AC supply. An up-and-down multivibrator circuit is used to withstand 2X input voltage transients.

Input current and voltage are converted to telemetry-compatible signals by the use of current-measuring reactors CMR1 and CMR2. Transfer characteristics of these T/M outputs are illustrated on Figure 26.

6. V6 - Accelerator Supply

The thrustor accelerator is supplied from the SAAF, is unregulated, and in other respects, is just like the screen supply, V6 (except **for** lower steady state current rating). Figure 27 shows this supply together with associated telemetry circuits.

Analogous to the experience with V5, V6 regulation was found to be mainly influenced by leakage reactance. Figure 28 (regulation of breadboard V6) and Figure 29 (regulation of the production unit V6) illustrate the result of increasing insulation spacing and, hence, leakage reactance.

Figures 30 and 31 show the accelerator voltage and current telemetry output transfer characteristics.

7. V7, V8, V9 - Neutralizer Supplies

The neutralizer supplies form an independent system which operate whenever the power conditioner is commanded on. The neutralizer discharge is produced and controlled by what amounts to a small separate power conditioner and ion thrustor subsystem. The schematic diagram of the neutralizer supplies is shown on Figures 32, 33, and 34.

The neutralizer inverter (Figure 32) consists of the DTS 423 transistors (Q97, Q98) and associated magnetically coupled multivibrator circuit (T21, T22, etc.). Thermistor TH-2 provides sensing of Q97 case temperature. T21 is the output transformer of the neutralizer inverter.

a

Figure 33 shows the V7 (neutralizer cathode) supply. RMS sensing and control is accomplished by the squaring network (Figure 35) in much the same manner as was done in the case of the main thrustor cathode, V3. A magnetic amplifier (L9) is used to provide the actual power switching control of the V7 output. The current-limiting feature gives inherent overload protection.

Current regulation is well within specified requirements. Figures 36 and 37 show these excellent regulating characteristics.

To provide the desired telemetry indication of emission current, a current measuring reactor, CMR-3, is connected to one terminal of the neutralizer cathode. The output of this telemetry circuit versus emission current is shown on Figure 40. V7 and I7 telemetry performance is shown on Figures 38 and 39.

The neutralizer vaporizer heater supply (V8) is relatively low power. A series regulator circuit is used. Transistor Q99 is the series transistor, connected from the 40/60 VDC source to the centertap of the vaporizer heater transformer, T23. Current-limit control of I8 is implemented through CT18 and related circuits shown on Figures 32 and 34.

Regulation with line and load is well inside specified limits as can be seen from Figures 41 and 42. Figures 43 and 44 show V8/I8 telemetry.

Thte probe bias supply (V9) is obtained by energizing the probe bias transformer (T29) through the series resistor R433, Figure 34. The V9 supply is provided by rectification (CR400, CR401) and filtering (C95). A voltage multiplier is used to provide the initial high no load voltage needed to start the neutralizer discharge.

Probe bias voltage is sensed by winding 3-4-5 of T29. Closed-loop control of V8 is obtained by error-amplification at Q105 - Q104 and control of the regulator transistor Q99. Figure 45 shows the high-gain control characteristic obtained.

Figure 46 shows the load-voltage characteristic of V9. Figure 47 gives the V9 telemetry transfer characteristic.

The array of diodes shown on the schematic Figure 34 is used to provide interconnection (with transient surge protection) among the various grounds in the system.

8. Control/Logic Circuit

Figures 48 and 49 contain the control/logic circuits, together with the series regulator circuit and level changer associated with the control functions.

On-off commands are by panel mounted pushbuttons (S11, S12). These switches actuate the reset coil of relay K5. Indicator lamps (DS1, DS2) are in turn energized through K5 contacts. These lamps verify the status of the input command signals.

The level changer is a means for transferring data from circuits with one ground reference to circuits referenced to a different ground. In this case, the level changer transfers overload trip signals from the telemetry circuits (I4, I5, I6) to the overload integrator (Q9, Q11, Q12). A series of faults or an overload on one or more of the V4, V5, or V6 supplies for an interval of 10 to 30 seconds results in pulse conduction of UJT Q11. This in turn energizes K5, turning the power conditioner off. Operation is restored by manually resetting K5 by S11. The level changer transformer T3 is supplied with the necessary AC excitation from the bias inverter, which was previously discussed. The same bias inverter transformer secondary supplies (by rectification) the -11.5 VDC and -23.0 VDC biases.

A single flip-flop or binary produces the control signals to the main SAAF inverter and, via an R-C delay circuit, to the Feed Clamp. A unijunction timer circuit, adjustable for delays from 0.01 to 1.0 second, recycles the binary after tripping. This UJT timer is set to produce the desired recycle rate. Figure 50 shows an oscilloscope trace of the recycle pulses with a screen-accelerator fault.

POWER CONDITIONER PERFORMANCE

During the last quarter of 1966, testing was performed in the 1NW NASA-LeRC test facility with the final-configuration ion thrustor. Well over 100 hours of operation were accumulated and much experience was gained relating to the power conditioner/ion thrustor system.

Appendix A includes strip chart recordings obtained during a small portion of these tests. A point of particular significance is that, for this test run, the power conditioner DC input was provided by a solar cell array simulator. The DC supply was programmed to simulate closely the V-I characteristic of a typical space vehicle solar cell array. As one might expect, operation with the simulator source, rather than a fixed voltage source, presents somewhat different operating conditions, particularly in the area of arcing/recycling. Successful operation as evidenced by these strip-charts is an important step in the project.

Efficiency

Efficiency of the final power conditioner was measured at 75% rated load. The specification requirement for efficiency at this condition is 80% minimum, and the power conditioner was found to meet the requirement. On the other hand, it is apparent from the data (Figure 51) that there is very little margin in meeting the required efficiency. The application of recently available fast switching power transistors and other like improvements would make possible considerable improvements in power conditioner efficiency.

PRODUCTION UNITS

The two sets of production equipments were furnished. Each power conditioner consists of four 19" rack mounted units. Construction is dead front, all connections being made to rear-mounted terminal strips.

Interconnections between the modular chassis are profided by interconnection wire harnesses which were furnished with the power conditioners.

The attached photographs Figures 52, 53, 54, 55 and 56 show front-panel views of each assembly and a view of the complete power conditioner interconnected, and operating into the Test Console/Dummy Load.

These units are of high quality construction and are easy to modify or service.

DUMMY LOAD TEST CONSOLE

In accordance with the contract, a Dummy Load Test Console was designed and built to enable complete checkout of the power conditioners. It included setting and operation of the several closed-loop controls, This Test Console is a self-contained laboratory test drive. It is floor mounted on castors. It has a double rack with standard 19" panels and rear door access. Figures 57 and 58 show views from the front and rear respectively.

The circuit diagram is included as Figure 59. Referring to this diagram, note that provision is made for simultaneous loading and metering of the power conditioner outputs. RF ammeters and voltmeters (thermocouple-actuated) are used to provide true RMS metering of the high frequency non-sinusoidal AC loads. A mercury vapor thyratron is included to simulate arcs between outputs and from outputs to ground. Air-cooled 3-1000Z vacuum triodes are used to provide the adjustable high voltage V5 and V6 loads.

All switches and load control knobs are accessible at the front panels. Connections to the loads and meters are made via a matrix of binding posts. All meters are mounted behind Plexiglass panels and switch interlocks are used on each rear access door to minimize shock hazard.

Because of the lethal potentials produced by the power conditioner, appropriate care must be exercised during all tests. The frame of the Test Console must be firmly grounded by at least one braided grounding strap. Control switches and direct load adjustments are operated via braid-grounded linkages. These linkages avoid the possibility of the application of high potentials to the controls should insulation breakdown within the Test Console.

During the test program, an interesting possibility for really gross errors in the metering was detected and corrected. It was found that effective electrostatic shielding for the floating HV metering must be provided. The RF meters used were not provided with such shielding. To correct this situation, each of the RF meters was wrapped in aluminum foil, which was then connected to one terminal of the meter. This measure was completely effective.

FUTURE DESIGN IMPROVEMENTS

During the course of this contract, possibilities for various improvements have become apparent. A brief discussion of each suggestion follows:

1. Telemetry outputs. The requirement for 1K maximum output impedance proved to be restrictive. In order to meet the requirement that the control system remain undisturbed despite open or shorted T/M outputs, separate CT's were required at the current T/M statlons. An increase in allowable T/M output impedance of 10:1 or greater would permit the dual use of the control CT's for both control and T/M with resulting saving in weight and parts count reduction.

2. Application of Microcircuits. The state of the art of microcircuits is maturing rapidly. There are now several families of micro-circuits which would profitably be applied to future power conditioner designs. The Control/logic section could utilize circuits from the so-called 930 DTL series - for example the latching section of the inverter control binary could be a single type 945 operated synchronously. Timing functions could be performed synchronously using clocked down-counting (single-circuit modules 16 counters are now readily available), or by analog means (such as by using a 709 operational amplifier in a fast reset integrator connection].. The application of presently-available prove IC's could contribute significantly to reduced weight and size and reduce slightly overall power losses.

3. Multifunction low-power drive inverter. The present power conditioner design is the logical outcome of a program in which flexibility was necessarily stressed, resulting in less than optimum system integration. For future equipments, the functions of the bias inverter, neutralizer inverter, and main inverter driver could easily be combined, resulting in a significant improvement in efficiency and reduction in weight and parts count.

4. Output rating. Again, for flexibility purposes, the present equipment is rated to drive much heavier thrustor cathode and thrustor anode loads than actually exist with the present thrustor. design. Obviously, a more closely-rated power conditioner would result in significant weight/size savings.

5. Operating frequency. The present power conditioner inverters operate in the 2-4 KHz frequency range. With the present availability of fast high voltage silicon power transistors, it appears that this operating frequency should be pushed upwards by a factor of 2 or 3:1, thereby resulting in a lighter-weight equipment.

6. Magnetic design. The problem encountered with achieving adequate HV insulation versus minimizing leakage reactances should receive more direct study on future development/design programs. Since the magnetic devices represent such a large proportion of size/weight of power conditioner electrical parts, this aspect of the deslgn should receive increasing emphasis in the future.

7. Accelerator impingement. During this program the control of the main mercury vaporizer (V2) was changed to limit beam current (I5) instead of accelerator impingement (I6). It is recommended that the addition of an "impingement override" loop be added to future designs. This would permit reduced-thrust operation should some unforeseen factor cause unusually-high accelerator impingement. This could be especially useful during initial operation while the accelerator is being "ion beam machined" to an optimum contour, and perhaps later on in the event of mercury deposition on the accelerator insulators, etc.

8. Main inverter transistor switching. Another very significant outcome of this program is the full realization of the importance of the "flux-rachetting" problem. Briefly, "flux-rachetting" refers to the tendency of the inverter output transformer to saturate at the end of each of one of the half cycles of operation, this being the result of inevitable asymmetries in 1/2 cycle conduction times, transistor saturation resistances, winding resistances, etc. The result of flux-rachetting is saturation current spikes on alternate half-cycles. These spikes can greatly increase transistor and output transistor heating. Of course, these current pulses are also very undesirable from the standpoint of the DC source.

   Referring to Figure 59, note that the primary winding of inductor L5 is effectively in series with the DC source current path through the inverter power switches and output magnetics. The function of L5 is to limit the rate of rise of the current through the input DC power path. Current "spikes" resulting from flux-rachetting are prevented. During transistor switching, the inherent turn-off storage time tends to result in an "overlap" interval during which all of the main inverter transistors can conduct simultaneously, L5 is also effective in preventing current pulses from occurring during the overlap interval, thereby further minimizing the peak collector currents during the interval of switching.

   Future power conditioner inverters should be carefully designed, perhaps as suggested here, to minimize the effects of flux-rachetting and overlap.

SERT II THRUSTOR CONTROL SCHEMATIC

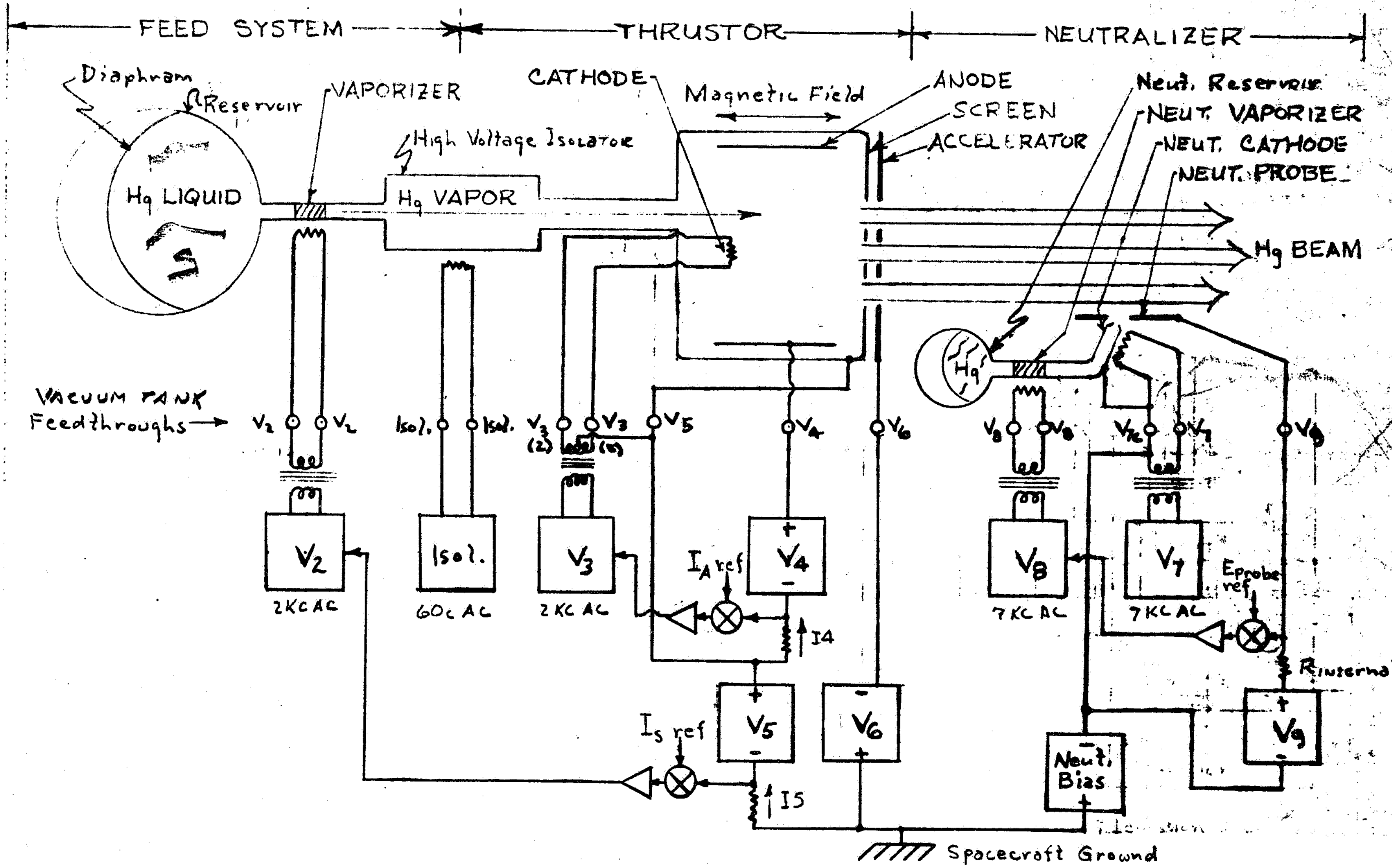


Fig. 1A

There is no V_1.
I4 & I5 pass thru current sensing resistors.
Note I5 controls V_2, I 4 controls V_3
V9 controls V_8

wrb 4/5/67

BY .... DATE .... SUBJECT .... SHEET NO. .... OF ....
CHKD. BY .... DATE .... JOB NO. ....

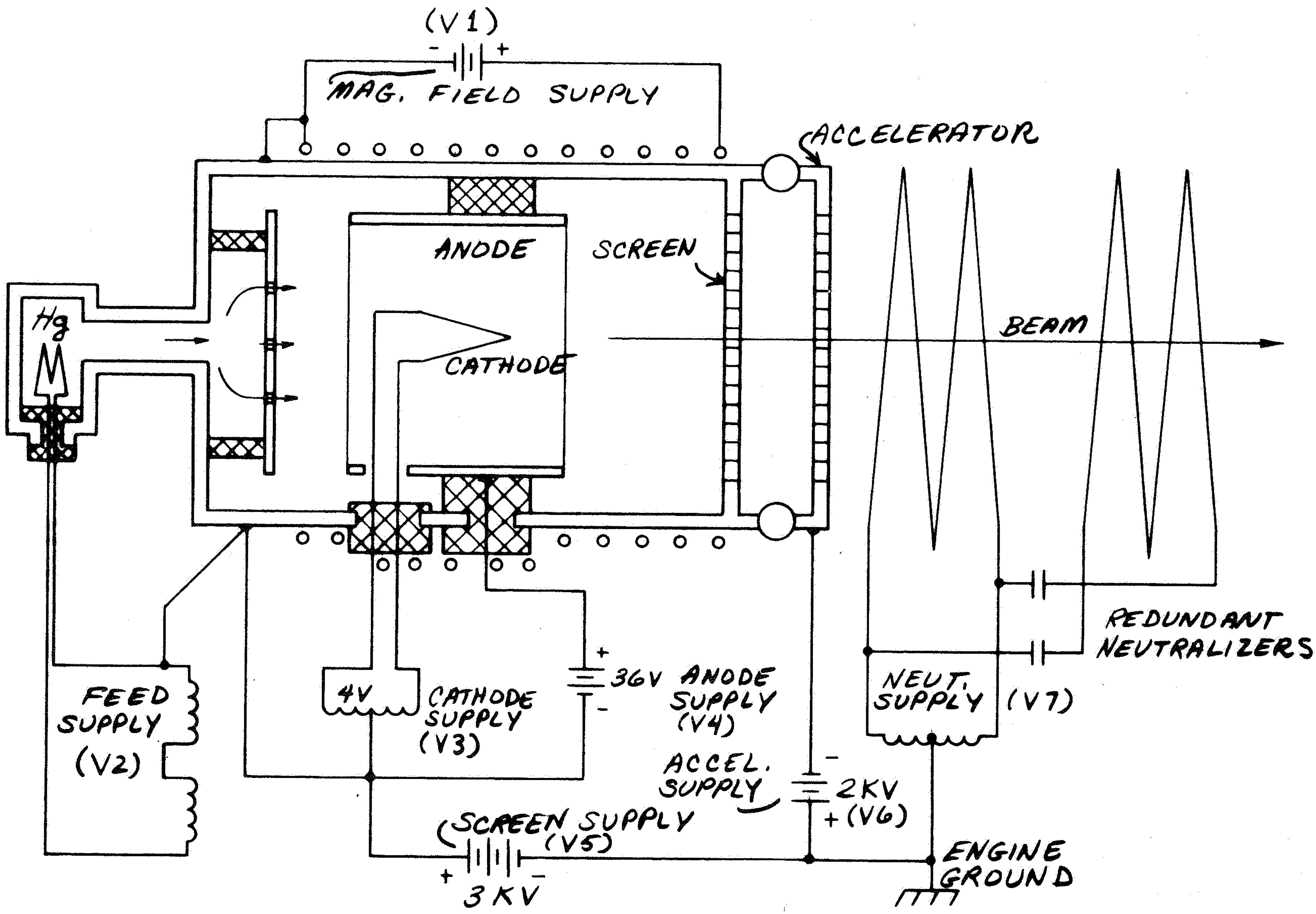
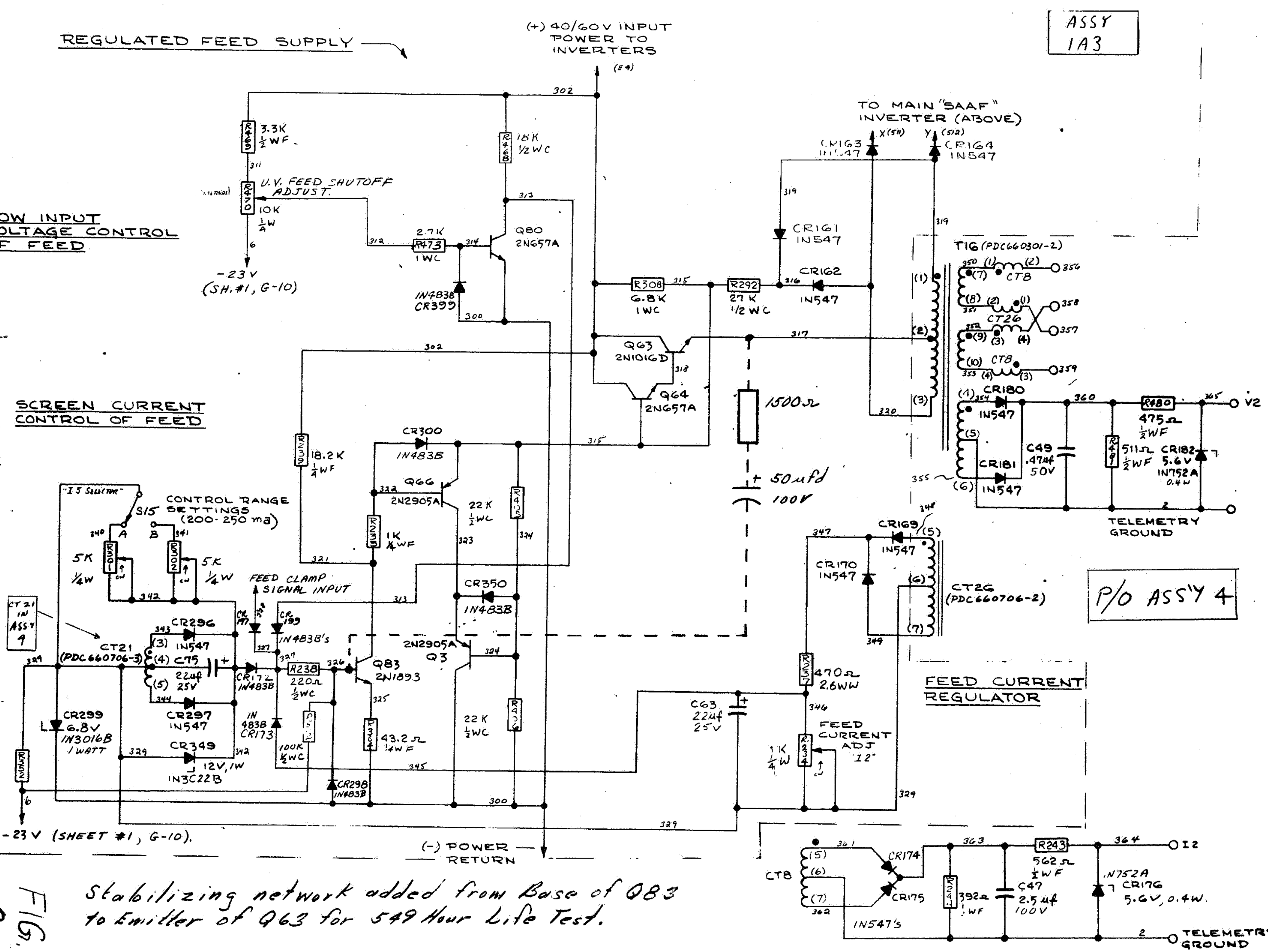

(V1)
MAG. FIELD SUPPLY
ACCELERATOR
Hg
ANODE
SCREEN
CATHODE
BEAM
REDUNDANT
NEUTRALIZERS
FEED
SUPPLY
(V2)
4V
CATHODE
SUPPLY
(V3)
36V ANODE
SUPPLY
(V4)
ACCEL.
SUPPLY
2KV
(V6)
NEUT.
SUPPLY
(V7)
SCREEN SUPPLY
(V5)
3 KV
ENGINE
GROUND

FIGURE 1B



REGULATED FEED SUPPLY
(+) 40/60V INPUT POWER TO INVERTERS
ASSY 1A3
TO MAIN "SAAF" INVERTER (ABOVE)
LOW INPUT VOLTAGE CONTROL OF FEED
U.V. FEED SHUTOFF ADJUST.
-23 V (SH.#1, G-10)
SCREEN CURRENT CONTROL OF FEED
CONTROL RANGE SETTINGS (200-250 ma)
FEED CLAMP SIGNAL INPUT
1500Ω
50 ufd 100V
TELEMETRY GROUND
P/O ASS'Y 4
FEED CURRENT REGULATOR
FEED CURRENT ADJ "I2"
-23 V (SHEET #1, G-10).
(-) POWER RETURN
Stabilizing network added from Base of Q83 to Emitter of Q63 for 549 Hour Life Test.

FIG. 2

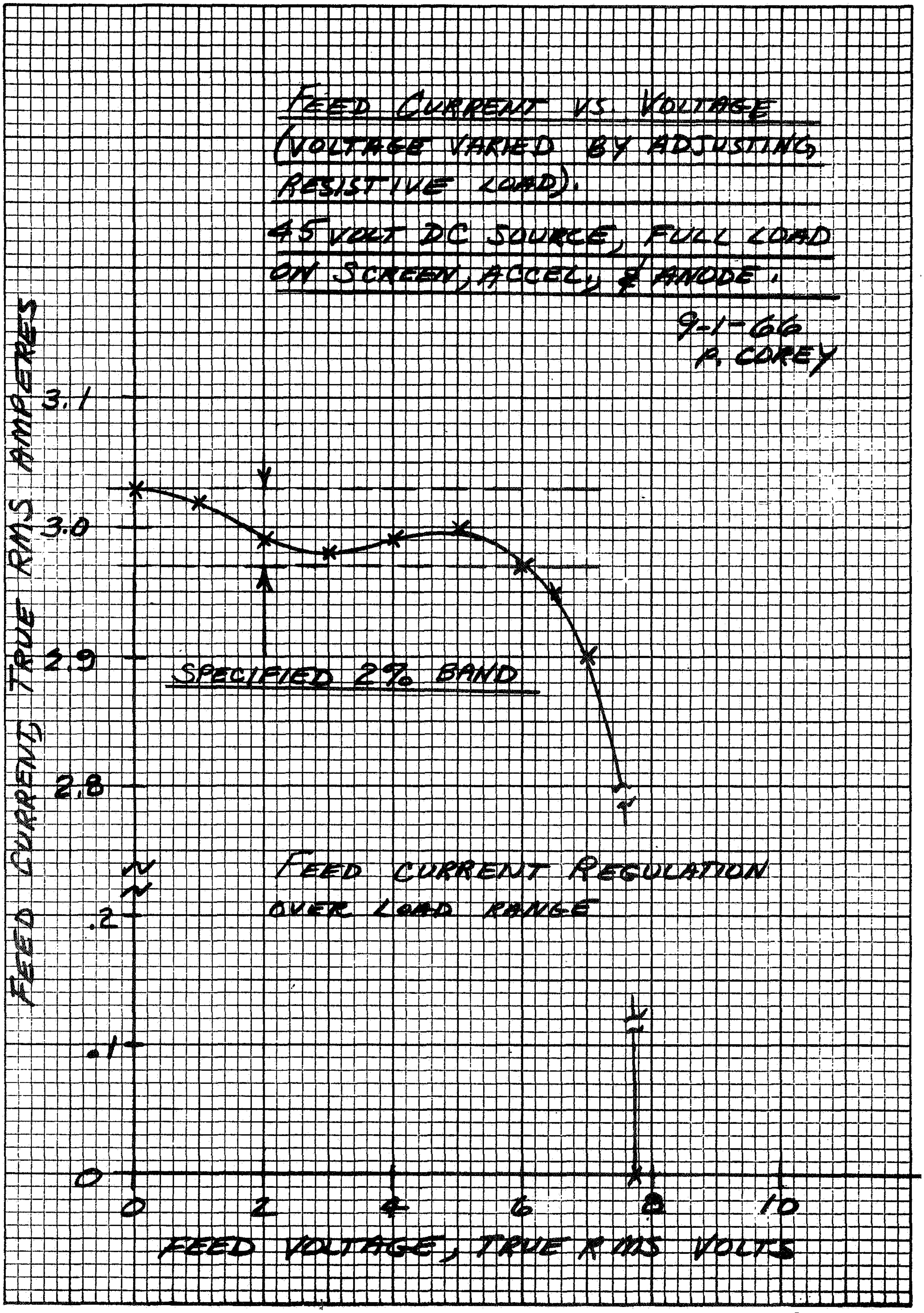
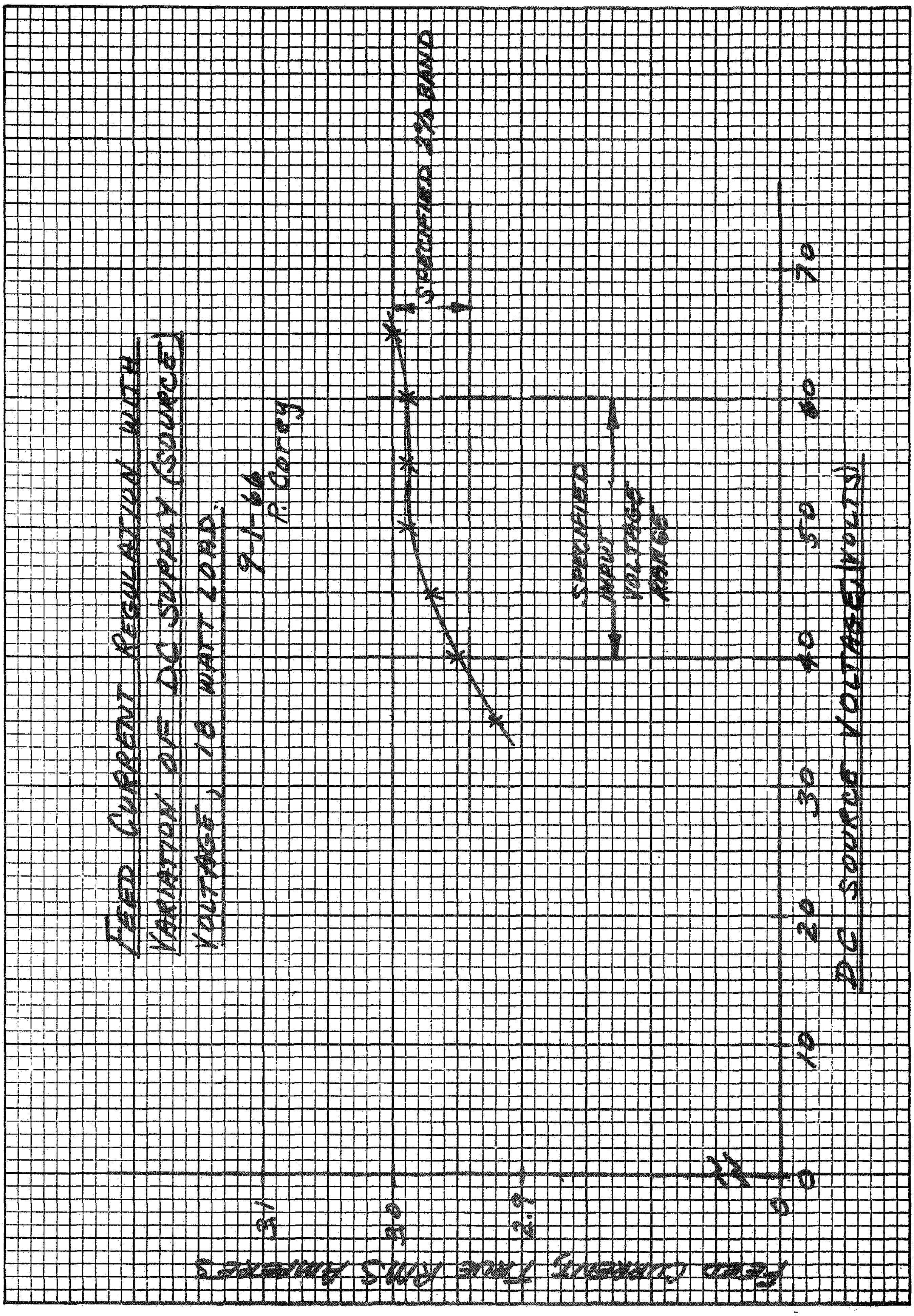

FEED CURRENT VS VOLTAGE
(VOLTAGE VARIED BY ADJUSTING RESISTIVE LOAD).
45 VOLT DC SOURCE, FULL LOAD ON SCREEN, ACCEL, & ANODE.
9-1-66
R. COREY
SPECIFIED 2% BAND
FEED CURRENT REGULATION OVER LOAD RANGE
FEED CURRENT, TRUE RMS AMPERES
FEED VOLTAGE, TRUE RMS VOLTS
3.1
3.0
2.9
2.8
.2
.1
0
0
2
4
6
8
10

FIG. 3.1



FEED CURRENT REGULATION WITH
VARIATION OF DC SUPPLY (SOURCE
VOLTAGE) 18 WATT LOAD
9-1-66
P. Corey
SPECIFIED 2% BAND
SPECIFIED
INPUT
VOLTAGE
RANGE
DC SOURCE VOLTAGE (VOLTS)
FEED CURRENT, TRUE RMS AMPERES
3.1
3.0
2.9
0
10
20
30
40
50
60
70

FIG. 4

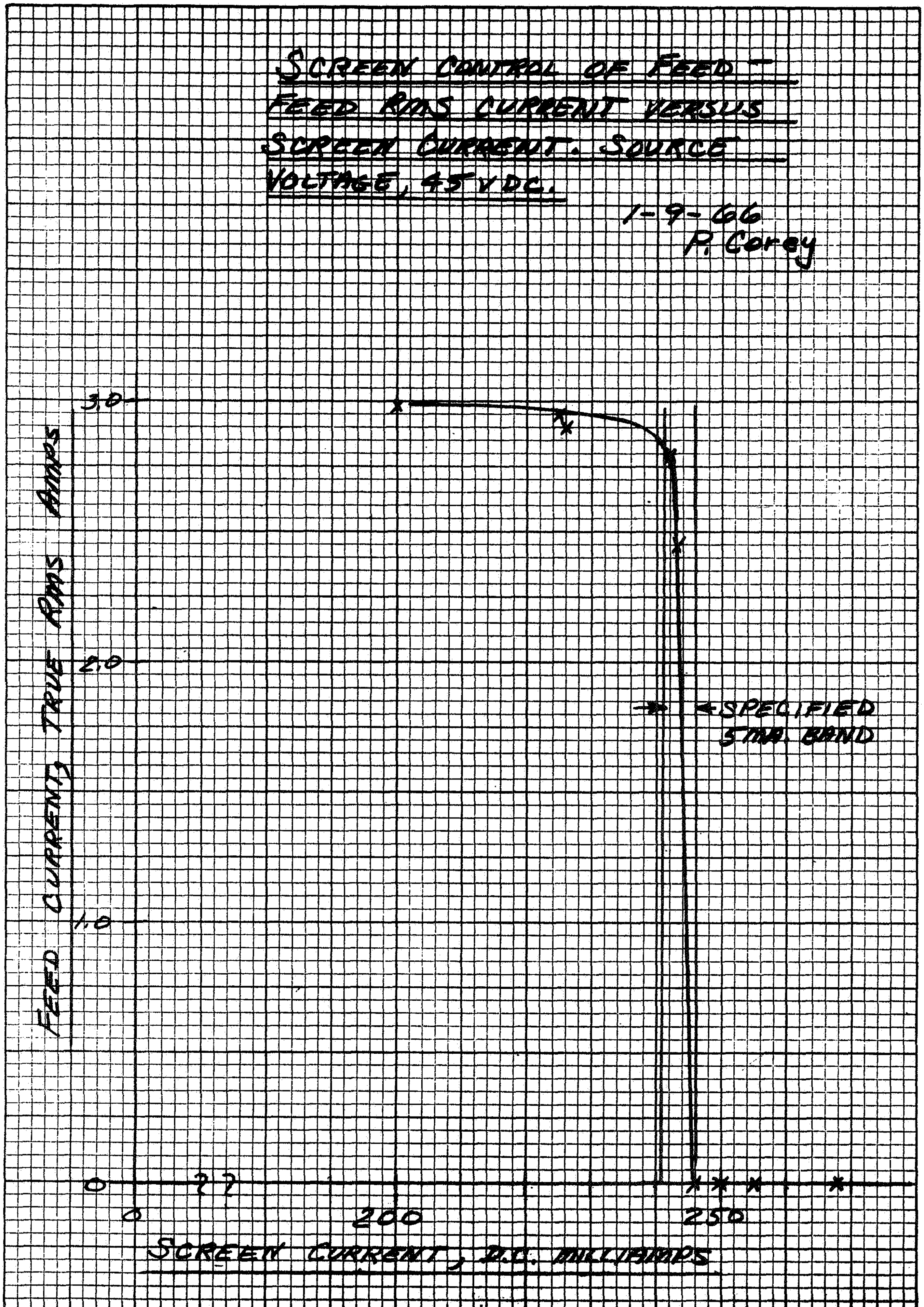
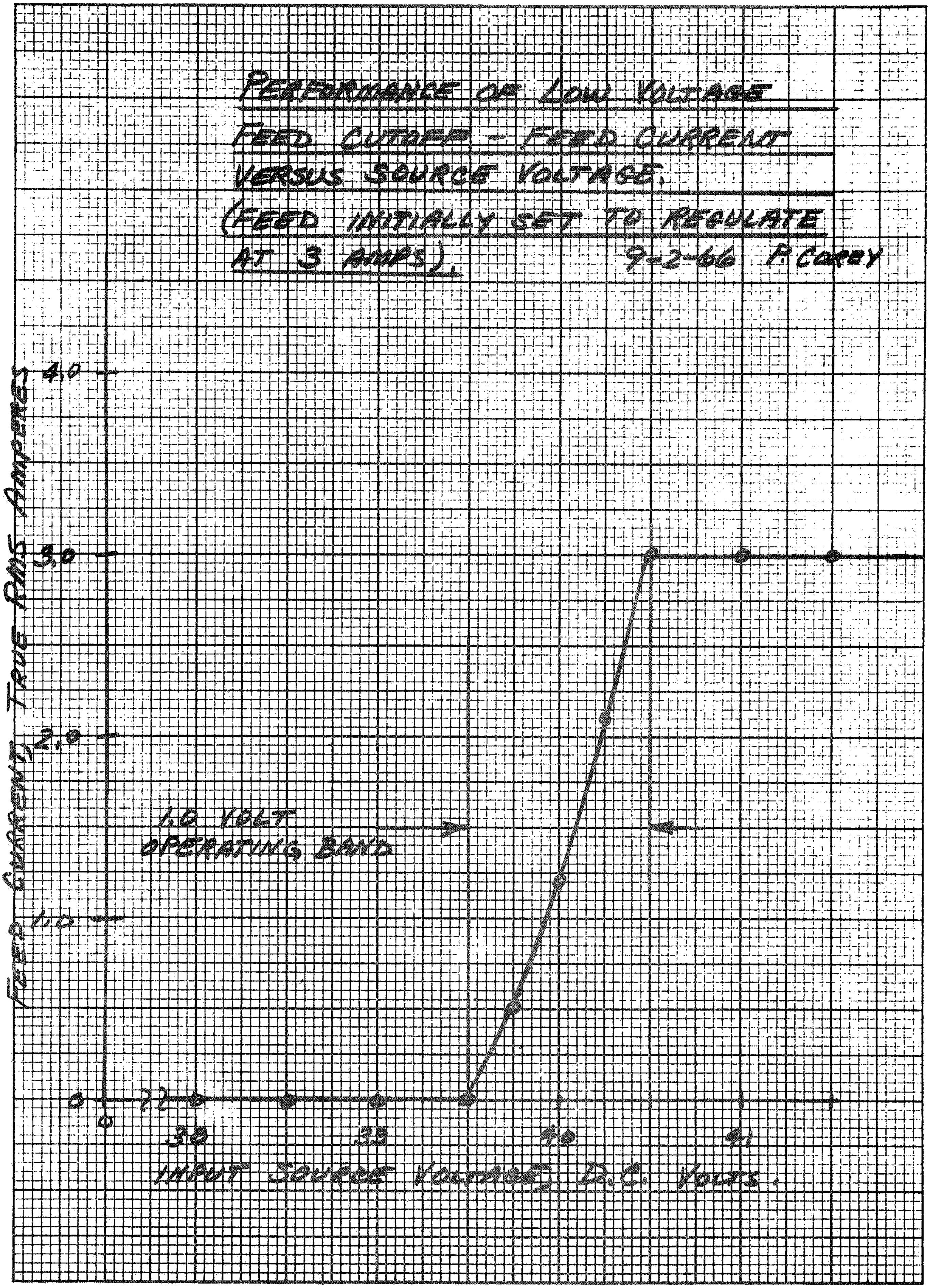

SCREEN CONTROL OF FEED - FEED RMS CURRENT VERSUS SCREEN CURRENT. SOURCE VOLTAGE, 45 VDC.
1-9-66
P. Corey
3.0
2.0
1.0
0
FEED CURRENT, TRUE RMS AMPS
SPECIFIED 5 MA. BAND
0
200
250
SCREEN CURRENT, D.C. MILLIAMPS

FIG. 5.



PERFORMANCE OF LOW VOLTAGE
FEED CUTOFF - FEED CURRENT
VERSUS SOURCE VOLTAGE.
(FEED INITIALLY SET TO REGULATE
AT 3 AMPS).
9-2-66 P. COREY
FEED CURRENT, TRUE RMS AMPERES
4.0
3.0
2.0
1.0
0
1.0 VOLT
OPERATING BAND
0
38
39
40
41
INPUT SOURCE VOLTAGE, D.C. VOLTS.

FIG. 6

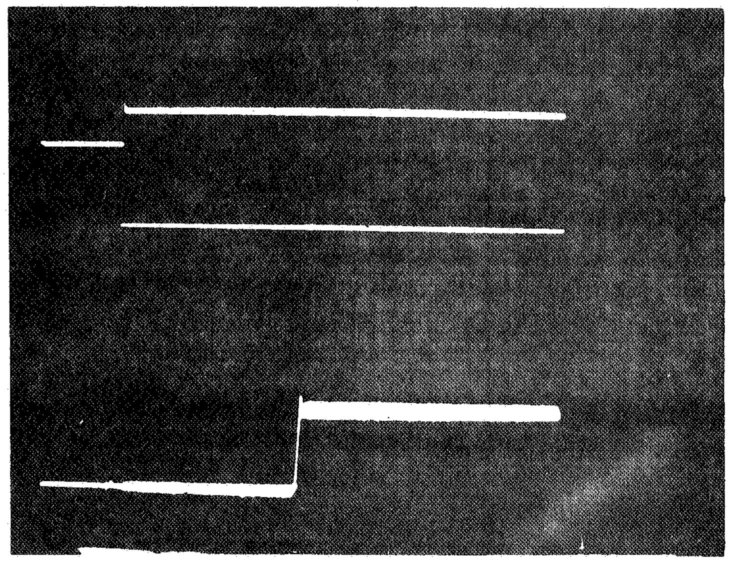


FIG. 7.

FEED TURN ON DELAY. TOP TRACE - COLLECTOR TO EMITTER OF Q61 & Q62 (SAAF), 50 VOLTS/CM. BOTTOM TRACE - (FEED) COLLECTOR OF Q83, 20 VOLTS/CM. HORIZONTAL SWEEP, 0.5 SEC./CM.

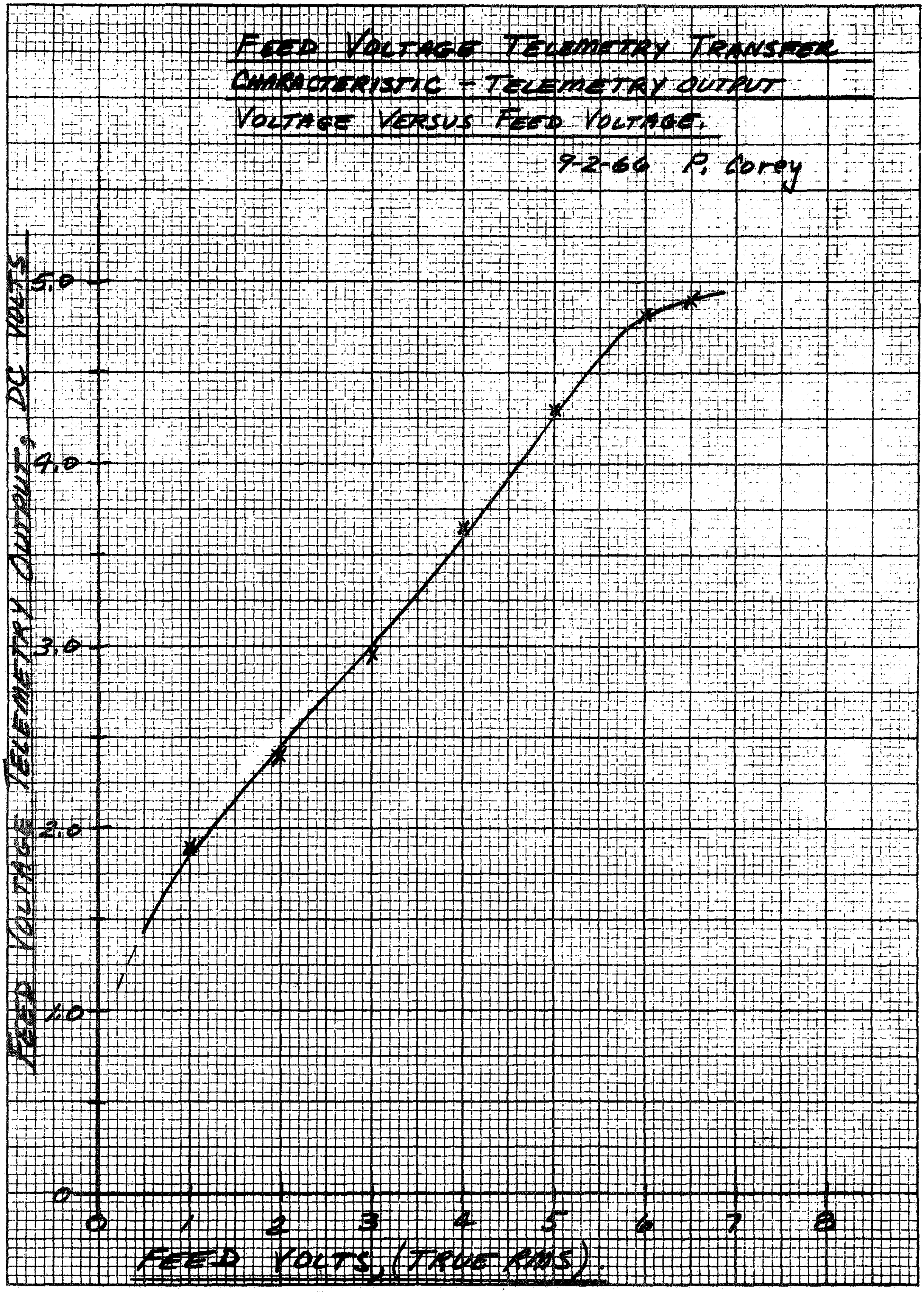

FEED VOLTAGE TELEMETRY TRANSFER
CHARACTERISTIC - TELEMETRY OUTPUT
VOLTAGE VERSUS FEED VOLTAGE.
9-2-66 P. Corey
FEED VOLTAGE TELEMETRY OUTPUT, DC VOLTS
5.0
4.0
3.0
2.0
1.0
0
0
1
2
3
4
5
6
7
8
FEED VOLTS, (TRUE RMS)

FIG. 8.

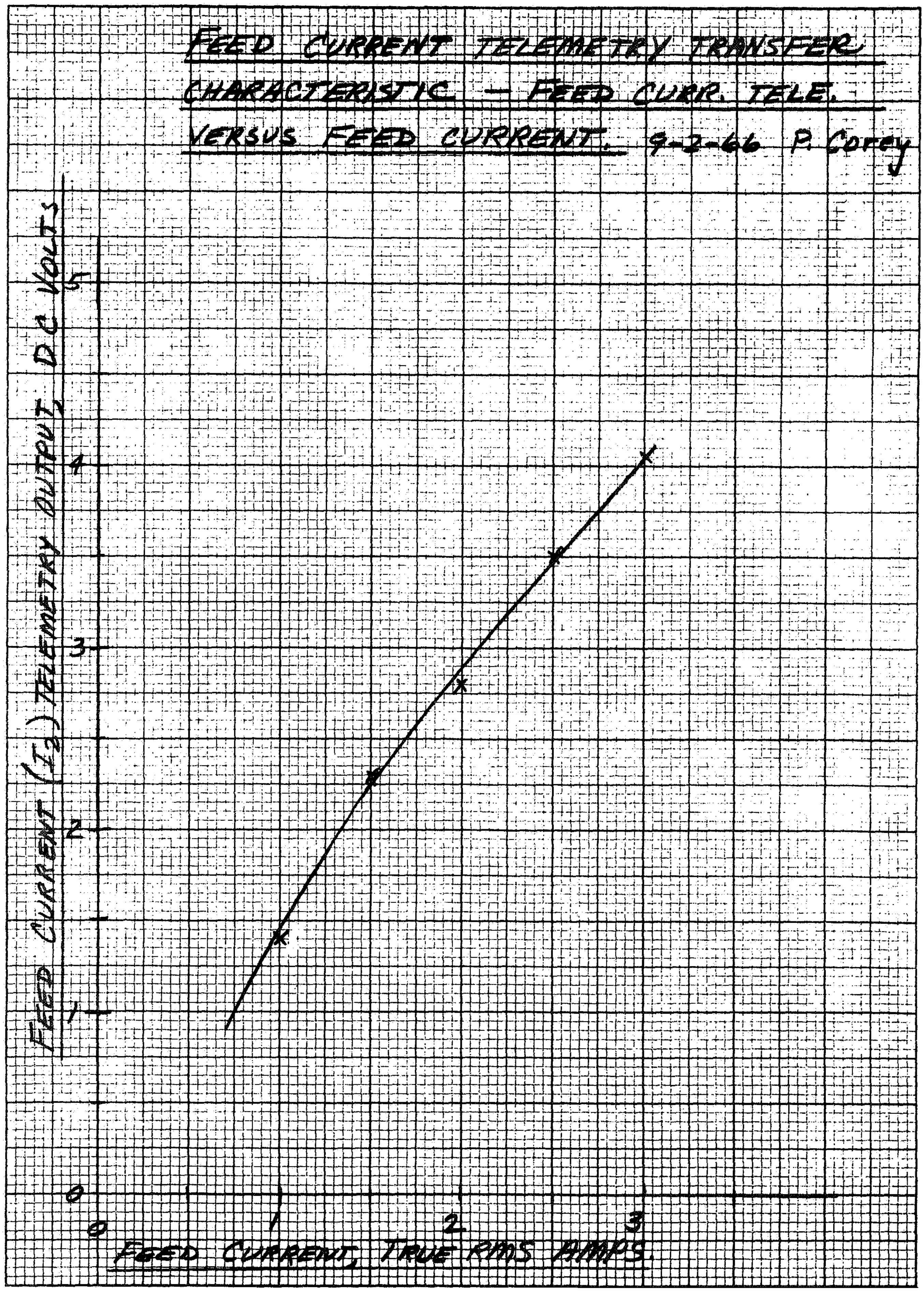

FEED CURRENT TELEMETRY TRANSFER CHARACTERISTIC — FEED CURR. TELE. VERSUS FEED CURRENT. 9-2-66 P. Corey
FEED CURRENT (I_2) TELEMETRY OUTPUT, D C VOLTS
FEED CURRENT, TRUE RMS AMPS.
0
1
2
3
4
5

FIG. 9.

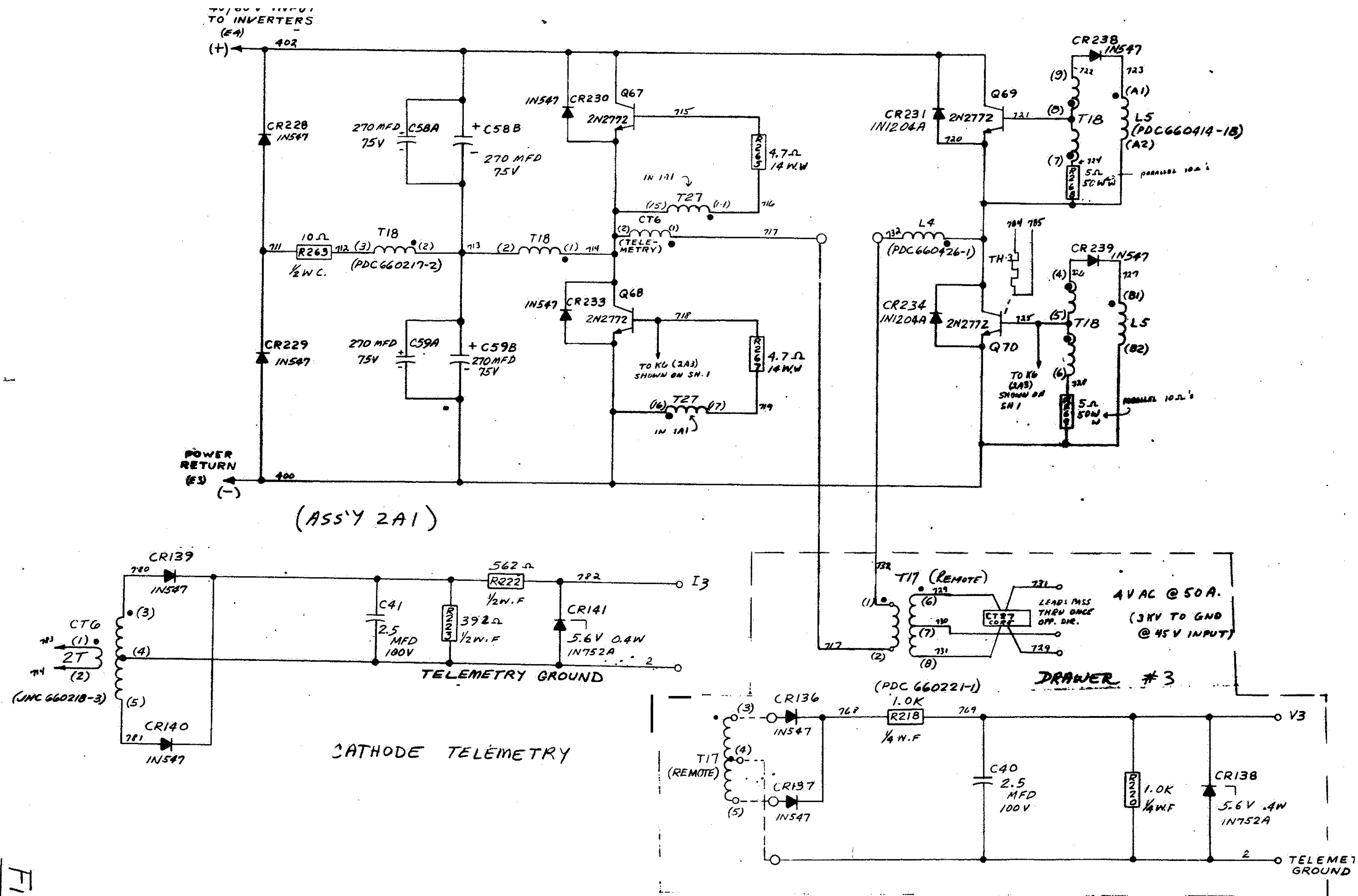

TO INVERTERS
(E4)
(+)
402
POWER RETURN
(E3)
(−)
400
CR228
IN547
CR229
IN547
10Ω
R263
½W C.
T18
(PDC660217-2)
270 MFD
C58A
75V
+ C58B
270 MFD
75V
270 MFD
C59A
75V
+ C59B
270 MFD
75V
IN547
CR230
Q67
2N2772
4.7Ω
R265
14 W.W
IN 1A1
T27
CT6
(TELE-METRY)
IN547
CR233
Q68
2N2772
TO K6 (2A3) SHOWN ON SH. 1
4.7Ω
R267
14 W.W
IN 1A1
CR231
IN1204A
Q69
2N2772
CR238
IN547
T18
L5
(PDC660414-1B)
5Ω
R268
50 W.W
PARALLEL 10Ω's
L4
(PDC660426-1)
TH-3
CR234
IN1204A
2N2772
Q70
TO K6 (2A3) SHOWN ON SH 1
CR239
IN547
T18
L5
5Ω
R269
50W W
PARALLEL 10Ω's
(ASS'Y 2A1)
CR139
IN547
CT6
2T
(UNC 660218-3)
CR140
IN547
C41
2.5 MFD
100V
R223
392Ω
½W.F
562Ω
R222
½W.F
CR141
5.6V 0.4W
IN752A
I3
TELEMETRY GROUND
CATHODE TELEMETRY
T17 (REMOTE)
CT27
CORE
LEADS PASS THRU ONCE OPP. DIR.
4 V AC @ 50 A.
(3KV TO GND @ 45 V INPUT)
DRAWER #3
T17
(REMOTE)
CR136
IN547
CR137
IN547
(PDC 660221-1)
1.0K
R218
¼W.F
C40
2.5 MFD
100 V
R220
1.0K
¼W.F
CR138
5.6V .4W
IN752A
V3
TELEMETRY GROUND

FIG 10.

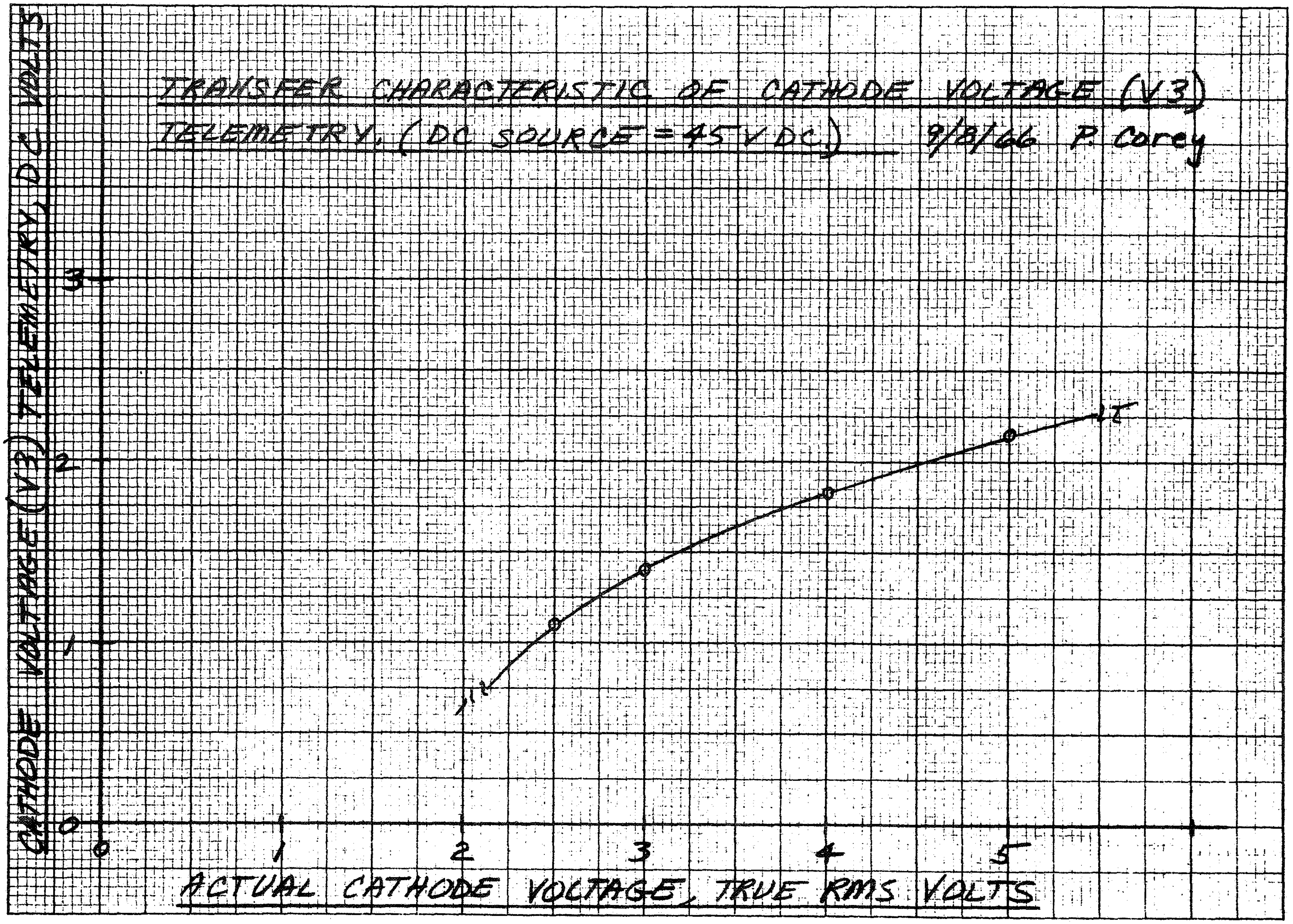

TRANSFER CHARACTERISTIC OF CATHODE VOLTAGE (V3)
TELEMETRY. (DC SOURCE = 45 V DC.)
9/8/66 P. Corey
CATHODE VOLTAGE (V3) TELEMETRY, DC VOLTS
ACTUAL CATHODE VOLTAGE, TRUE RMS VOLTS
0
1
2
3
4
5

FIGURE 11

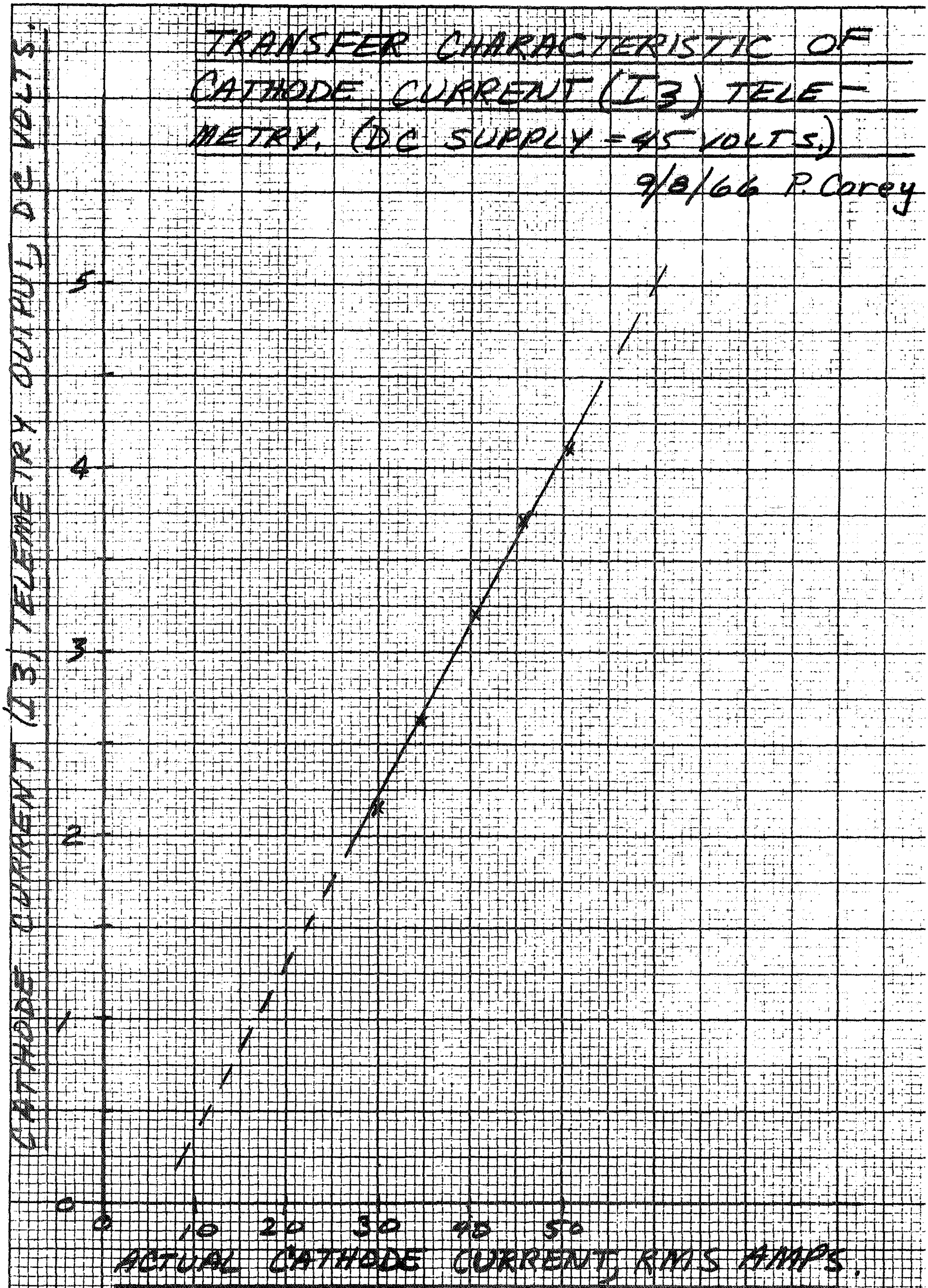
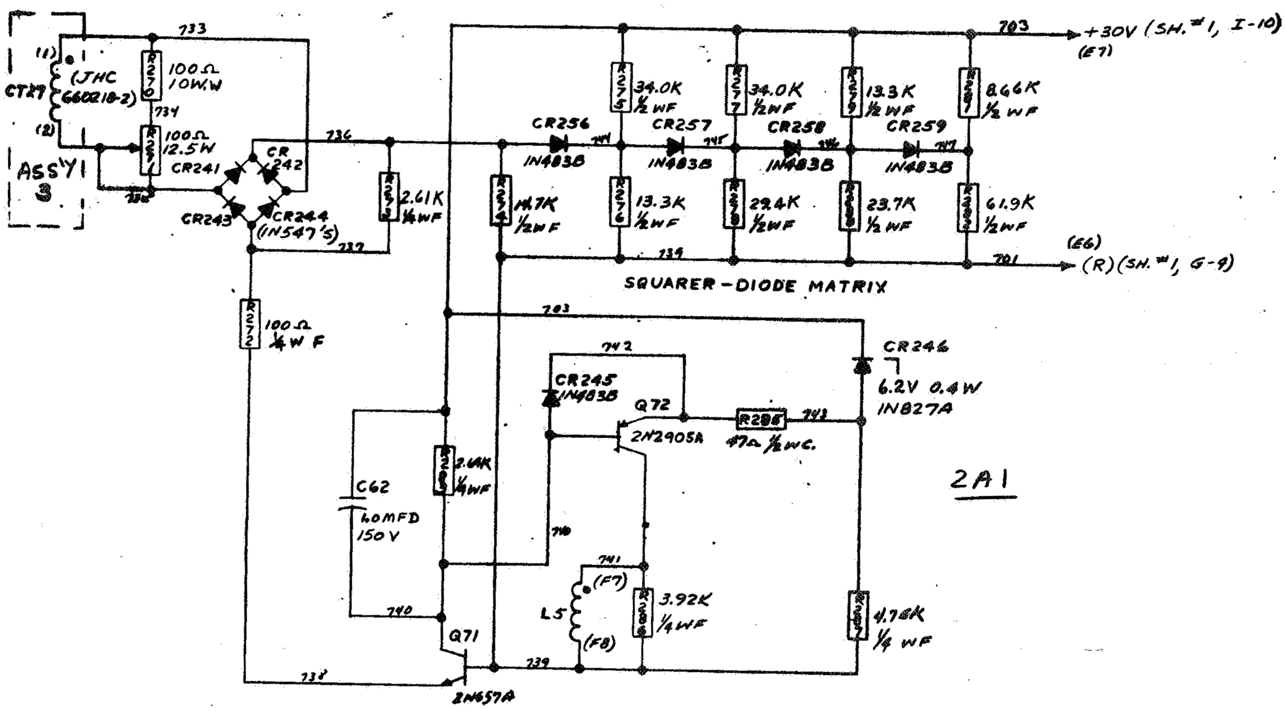

TRANSFER CHARACTERISTIC OF CATHODE CURRENT (I3) TELEMETRY. (DC SUPPLY = 45 VOLTS.)
9/8/66 P. Corey
CATHODE CURRENT (I3) TELEMETRY OUTPUT, DC VOLTS.
5
4
3
2
1
0
0
10
20
30
40
50
ACTUAL CATHODE CURRENT, RMS AMPS.

FIGURE 12

CATHODE

SQUARER-RMS SENSING



ANODE CONTROL OF CATHODE CURRENT

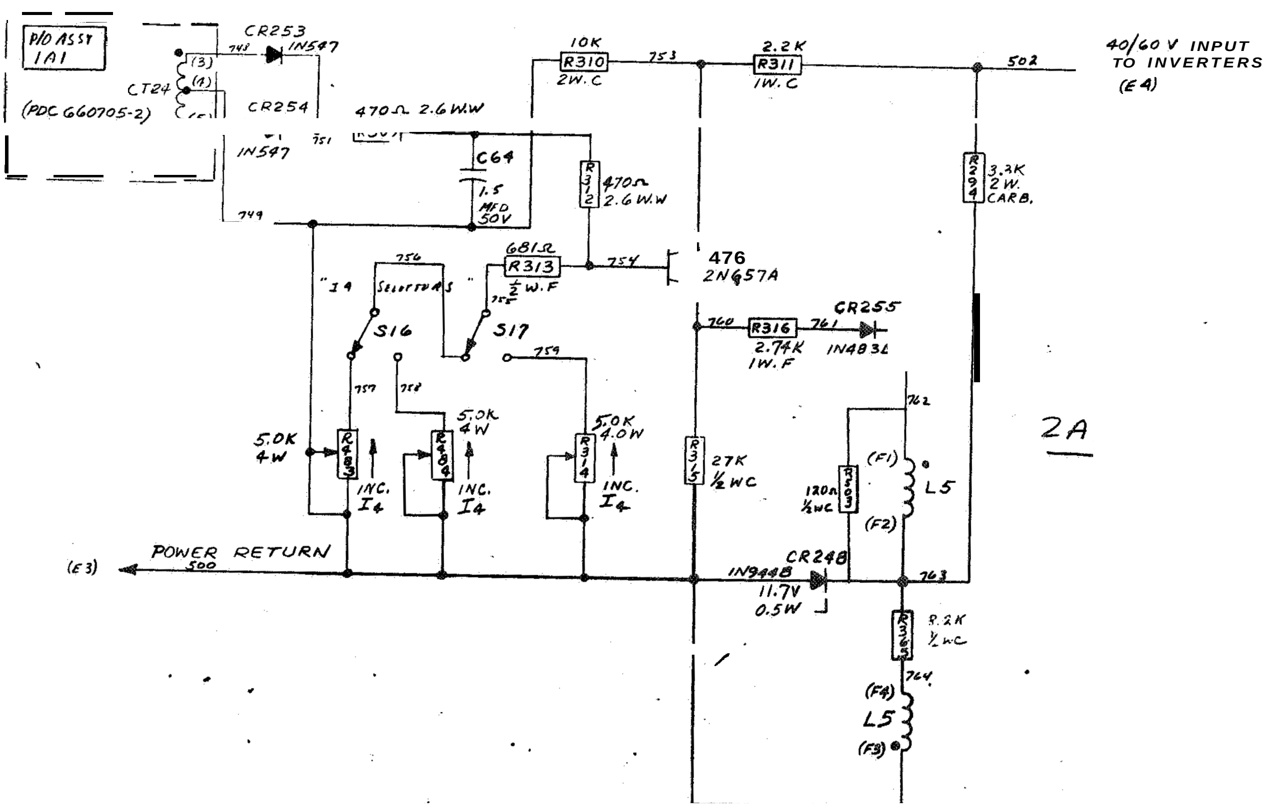
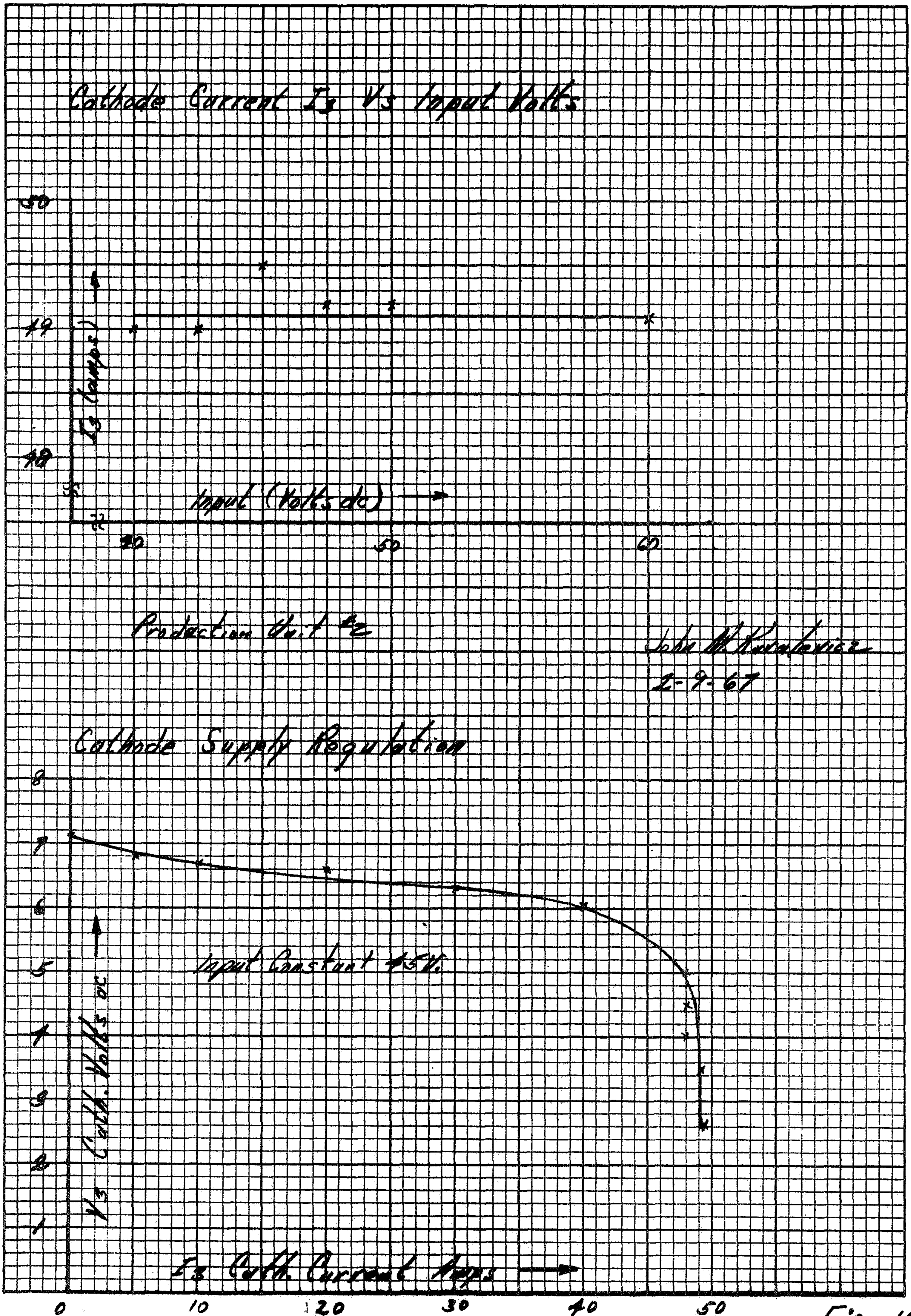
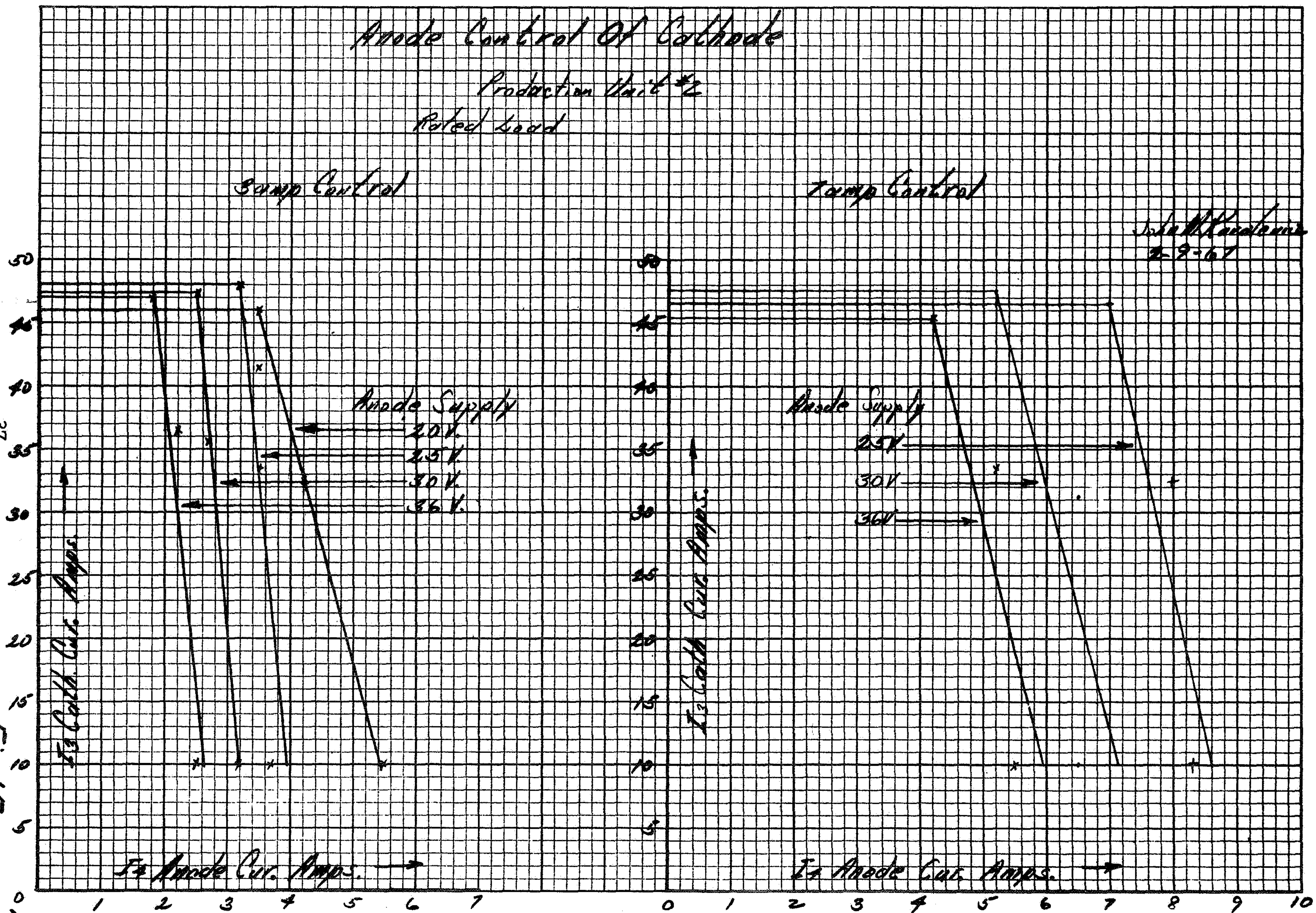


FIG. 13



Cathode Current I3 Vs Input Volts
50
49
48
Production Unit #2
John M Kuzalewicz
2-9-67
Cathode Supply Regulation
Input Constant 45V.
I3 Cath. Current Amps
8
7
6
5
4
3
2
1
0
10
20
30
40
50

Fig 14



Anode Control Of Cathode
Production Unit #2
Rated Load
3 amp Control
7 amp Control
John M. Karalanis
2-9-67
Anode Supply
20 V.
25 V.
30 V.
36 V.
Anode Supply
25 V
30 V
36 V
I3 Cath. Cur. Amps.
I4 Anode Cur. Amps.
I3 Cath. Cur. Amps.
I4 Anode Cur. Amps.
50
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
0
1
2
3
4
5
6
7
8
9
10

Fig. 15

4-4

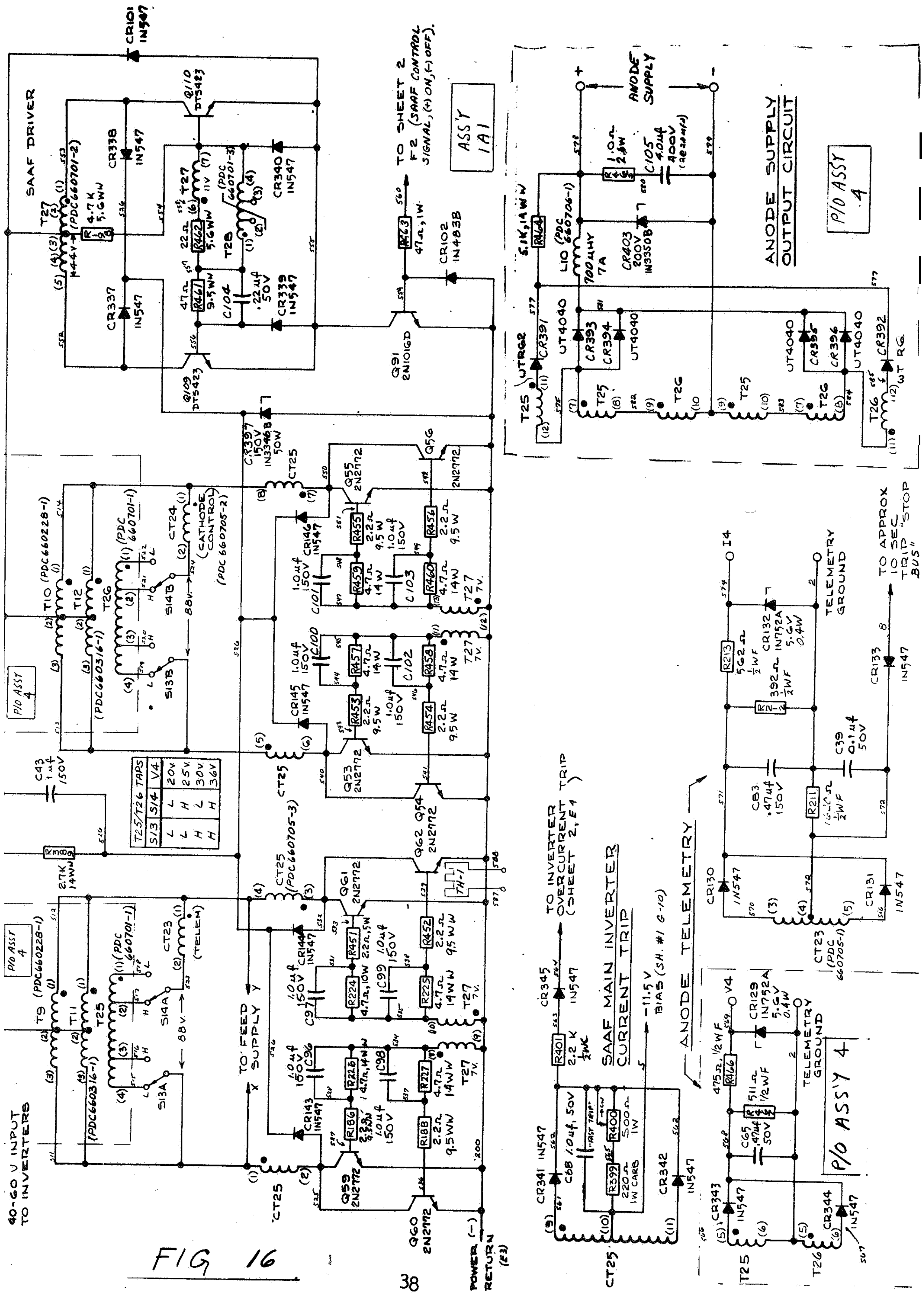
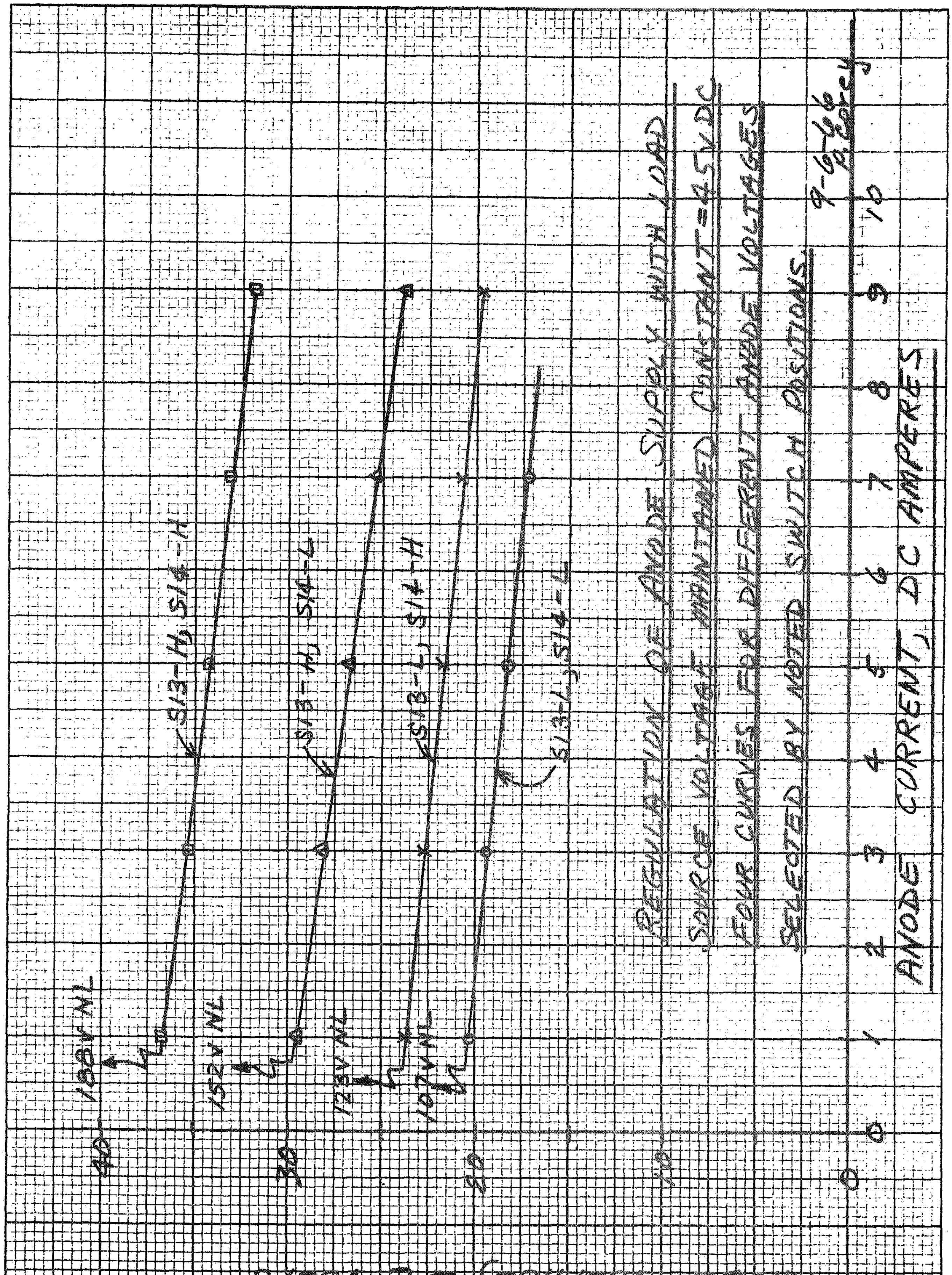

SAAF DRIVER
TO SHEET 2 F2 (SAAF CONTROL SIGNAL, (+) ON, (-) OFF).
ASS'Y 1A1
ANODE SUPPLY
ANODE SUPPLY OUTPUT CIRCUIT
P/O ASSY 4
40-60 V INPUT TO INVERTERS
TO FEED SUPPLY
POWER (-) RETURN (E3)
TO INVERTER OVERCURRENT TRIP (SHEET 2, E4)
SAAF MAIN INVERTER CURRENT TRIP
-11.5 V BIAS (SH. #1 G-10)
ANODE TELEMETRY
TELEMETRY GROUND
TO APPROX 10 SEC TRIP "STOP BUS"
P/O ASS'Y 4

FIG 16



REGULATION OF ANODE SUPPLY WITH LOAD
SOURCE VOLTAGE MAINTAINED CONSTANT = 45 V DC
FOUR CURVES FOR DIFFERENT ANODE VOLTAGES
SELECTED BY NOTED SWITCH POSITIONS.
188V NL
152V NL
123V NL
107V NL
S13-H, S14-H
S13-H, S14-L
S13-L, S14-H
S13-L, S14-L
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
ANODE CURRENT, DC AMPERES
ANODE VOLTAGE, DC VOLTS

FIGURE 17

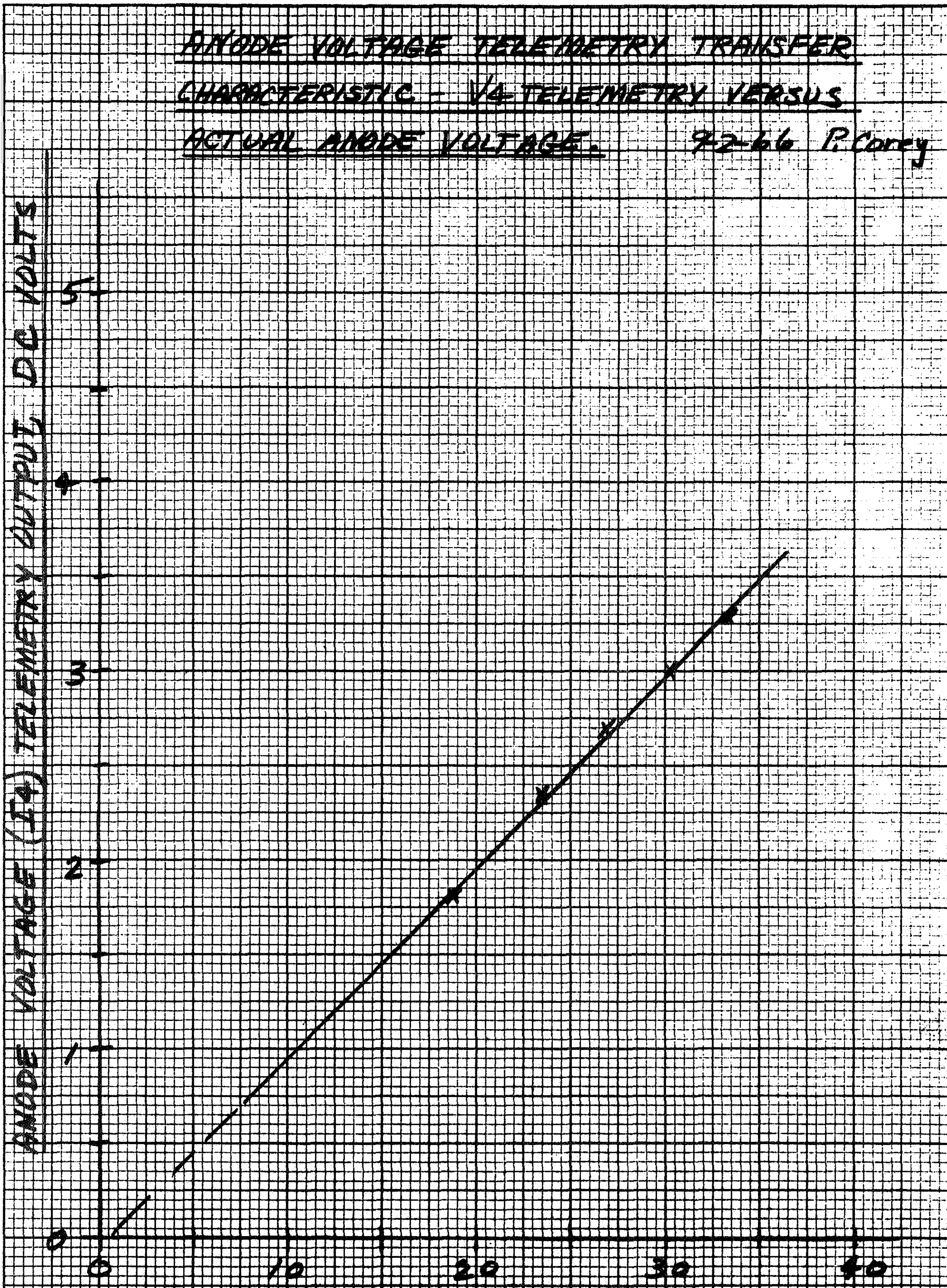

ANODE VOLTAGE TELEMETRY TRANSFER
CHARACTERISTIC - V4 TELEMETRY VERSUS
ACTUAL ANODE VOLTAGE. 9-2-66 P. Corey
ANODE VOLTAGE (V4) TELEMETRY OUTPUT DC VOLTS
0
1
2
3
4
5
0
10
20
30
40
ANODE VOLTAGE - DC VOLTS

FIG. 18

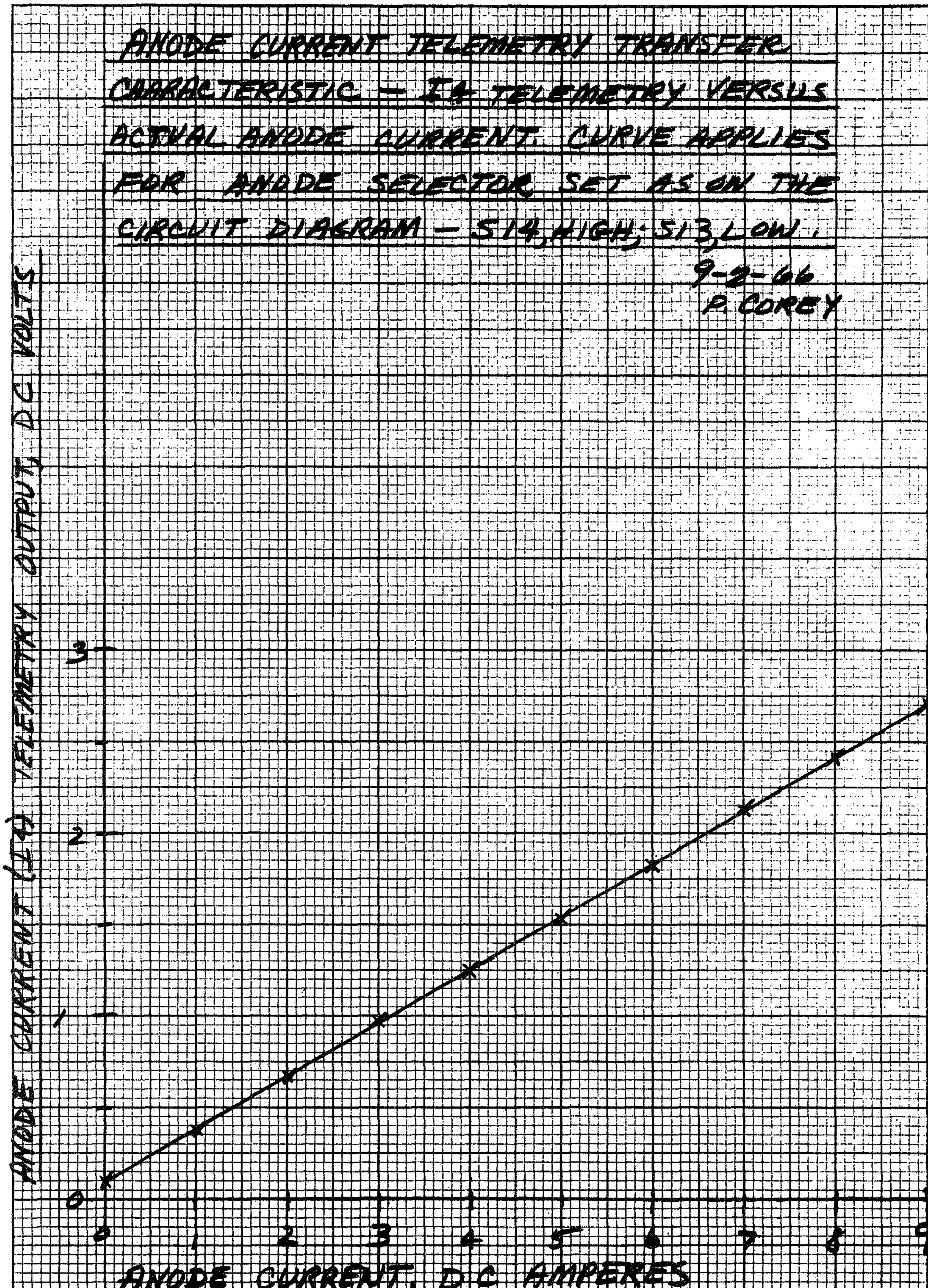

ANODE CURRENT TELEMETRY TRANSFER CHARACTERISTIC — I4 TELEMETRY VERSUS ACTUAL ANODE CURRENT. CURVE APPLIES FOR ANODE SELECTOR SET AS ON THE CIRCUIT DIAGRAM — S14, HIGH; S13, LOW.
9-2-66
P. COREY
ANODE CURRENT (I4) TELEMETRY OUTPUT, DC VOLTS
0
1
2
3
0
1
2
3
4
5
6
7
8
9
ANODE CURRENT, DC AMPERES

FIG. 19

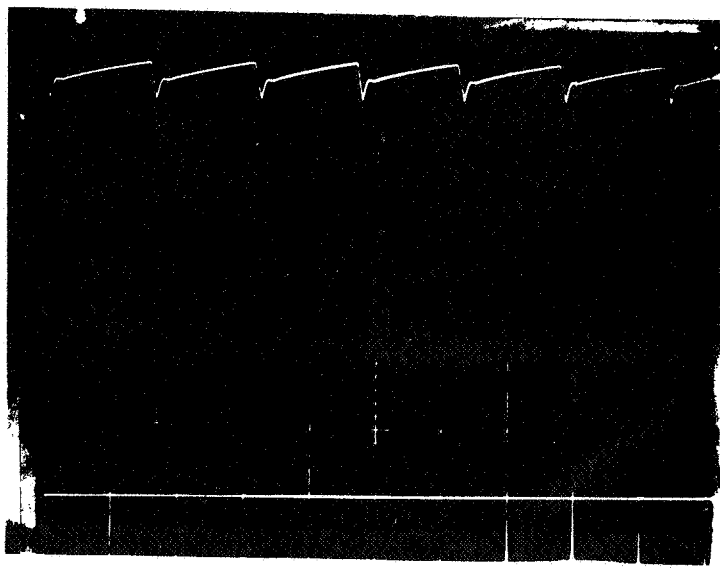
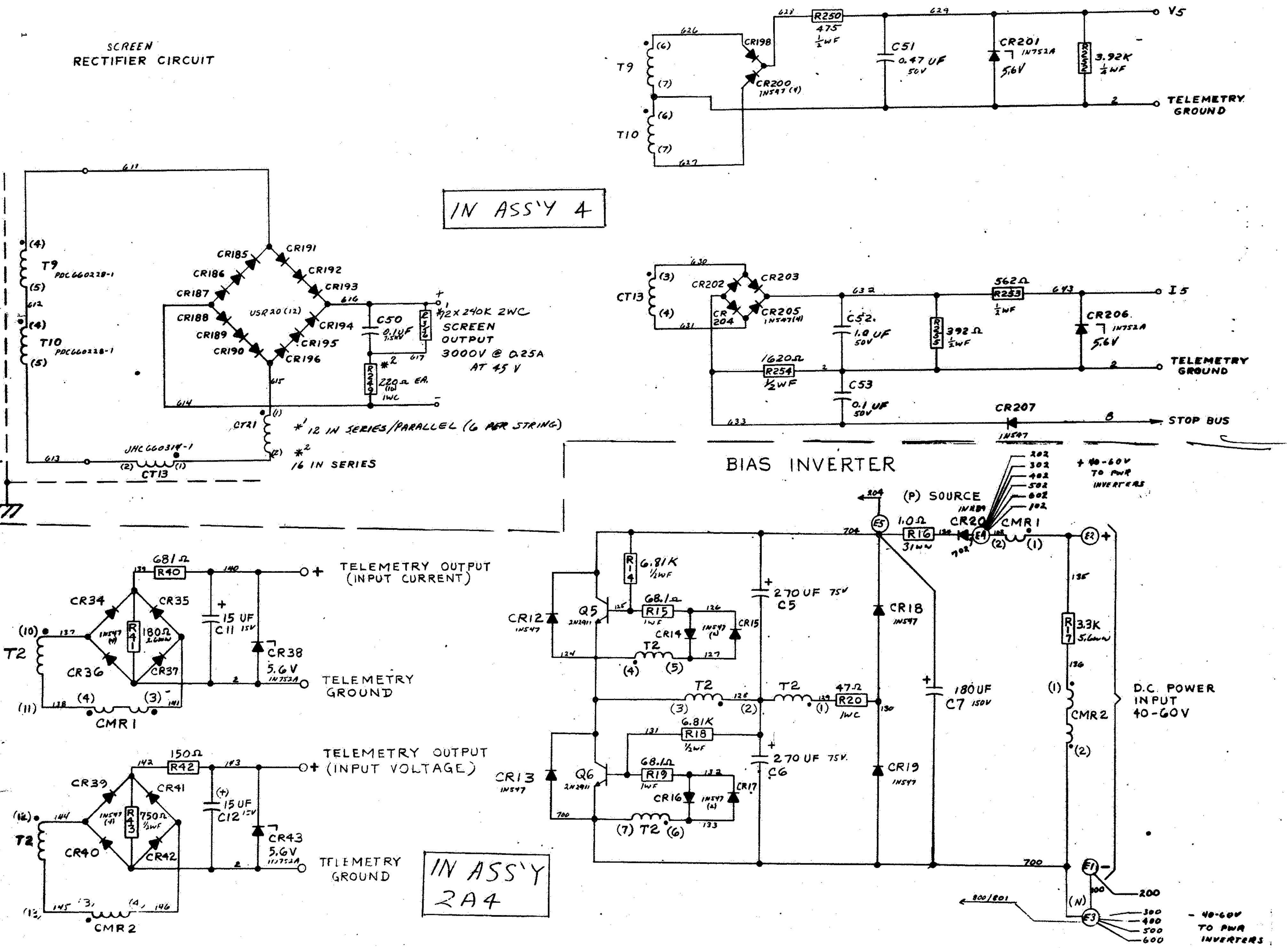


FIG. 20 ANODE VOLTAGE SHOWING RIPPLE AMPLITUDE. FULL 7 AMP LOAD, 45 VOLTS DC SUPPLY, SCALES: 5 VOLTS/DIVISION, 200μSEC/DIVISION.


SCREEN
RECTIFIER CIRCUIT
IN ASS'Y 4
IN ASS'Y 2A4
BIAS INVERTER
V5
I5
TELEMETRY GROUND
STOP BUS
T9
T10
CT13
CT21
PDC660228-1
JHC660314-1
CR185
CR186
CR187
CR188
CR189
CR190
CR191
CR192
CR193
CR194
CR195
CR196
USR20 (12)
C50 0.1UF 7.5KV
*1 12 x 240K 2WC
SCREEN OUTPUT
3000V @ 0.25A
AT 45 V
*2 220Ω EA. (16) 1WC
*1 12 IN SERIES/PARALLEL (6 PER STRING)
*2 16 IN SERIES
CR198
CR200 1N547 (4)
R250 475 1/2WF
C51 0.47 UF 50V
CR201 1N752A 5.6V
R252 3.92K 1/4WF
CR202
CR203
CR204
CR205 1N547(4)
C52 1.0 UF 50V
R255 392Ω 1/2WF
R253 562Ω 1/2WF
CR206 1N752A 5.6V
R254 1620Ω 1/2WF
C53 0.1 UF 50V
CR207 1N547
(P) SOURCE
R16 1.0Ω 3.1WW
CR20 1N1184
CMR1
+ 40-60V TO PWR INVERTERS
R14 6.81K 1/2WF
Q5 2N2911
Q6 2N2911
CR12 1N547
CR13 1N547
R15 68.1Ω 1WF
R19 68.1Ω 1WF
CR14
CR15
CR16
CR17
T2
C5 270 UF 75V
C6 270 UF 75V
R18 6.81K 1/2WF
R20 47Ω 1WC
CR18 1N547
CR19 1N547
C7 180UF 150V
R17 3.3K 5.6WW
CMR2
D.C. POWER INPUT 40-60V
- 40-60V TO PWR INVERTERS
TELEMETRY OUTPUT (INPUT CURRENT)
TELEMETRY OUTPUT (INPUT VOLTAGE)
R40 681Ω
CR34
CR35
CR36
CR37
R41 180Ω 2.6WW
C11 15 UF 15V
CR38 5.6V 1N752A
R42 150Ω
CR39
CR40
CR41
CR42
R43 750Ω 1/2WF
C12 15 UF 15V
CR43 5.6V 1N752A

43

FIGURE 21

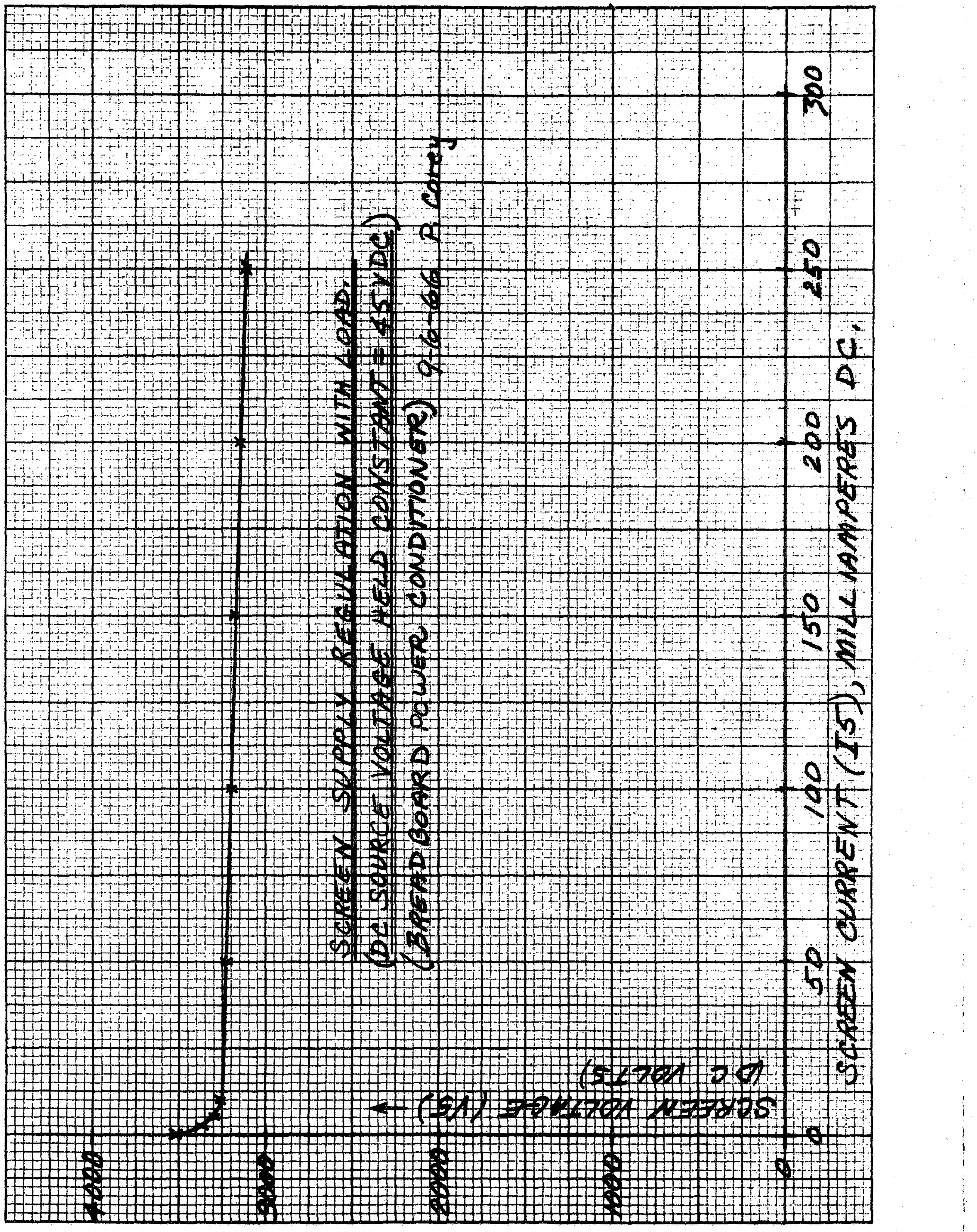

SCREEN SUPPLY REGULATION WITH LOAD.
(DC SOURCE VOLTAGE HELD CONSTANT = 45 VDC.)
(BREADBOARD POWER CONDITIONER) 9-6-66 P. Corey
SCREEN VOLTAGE (VS) (DC VOLTS)
4000
3000
2000
1000
0
50
100
150
200
250
300
SCREEN CURRENT (IS), MILLIAMPERES DC.

FIGURE 22

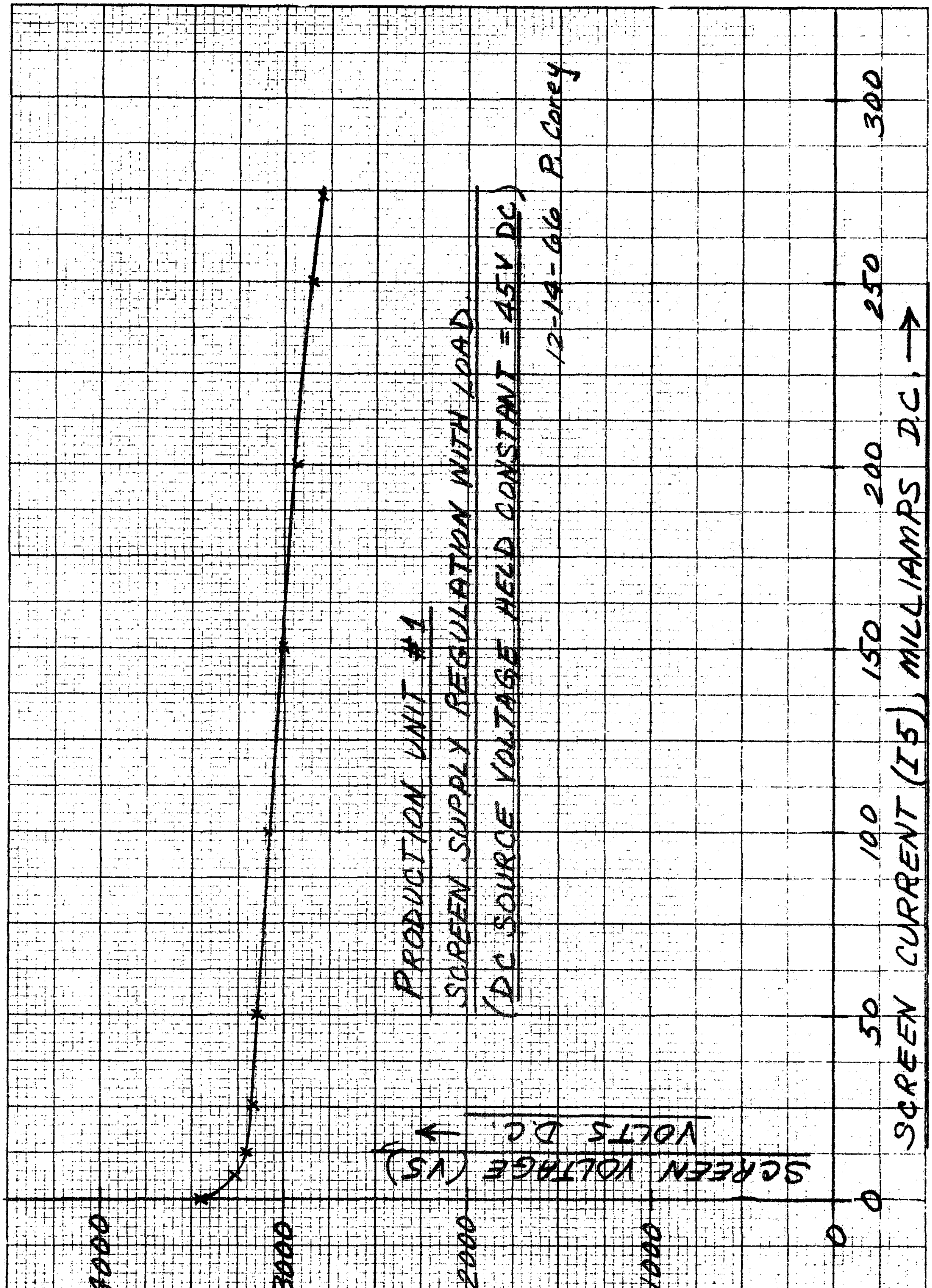

PRODUCTION UNIT #1
SCREEN SUPPLY REGULATION WITH LOAD
(DC SOURCE VOLTAGE HELD CONSTANT = 45V DC)
12-14-06 P. Corey
SCREEN CURRENT (IS) MILLIAMPS D.C.
0
50
100
150
200
250
300
SCREEN VOLTAGE (VS) VOLTS D.C.
4000
3000
2000
1000
0

FIG 23

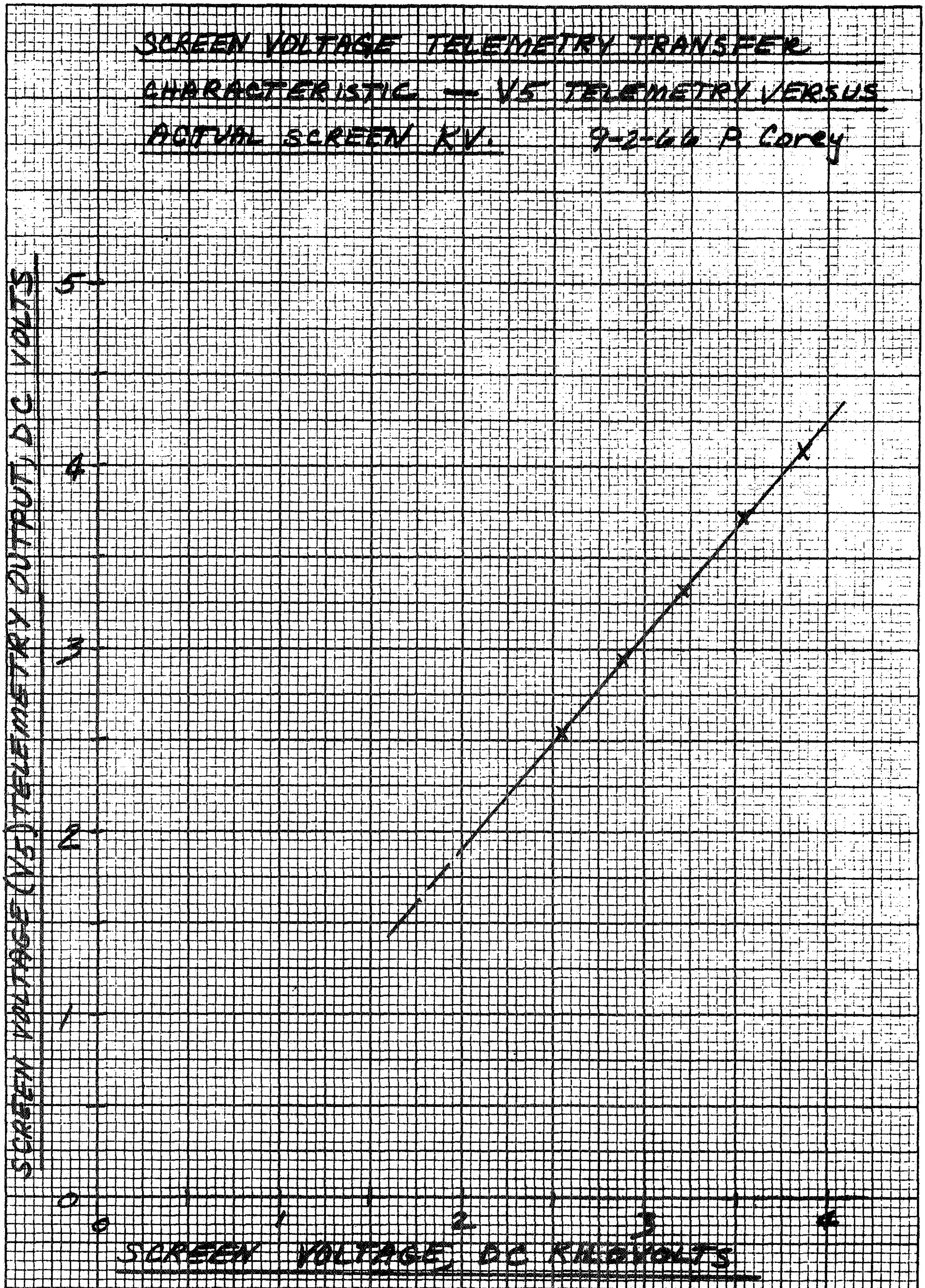
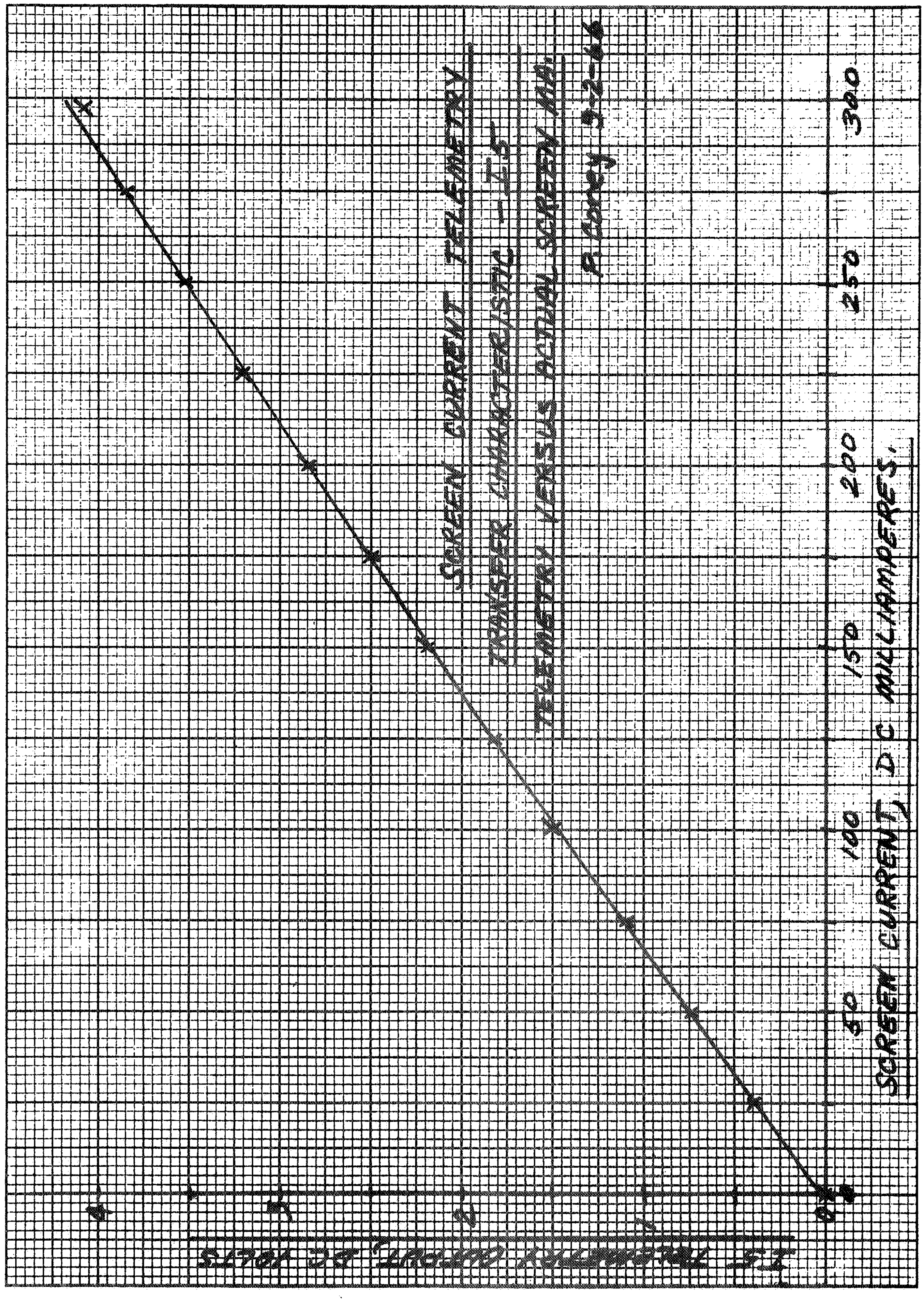
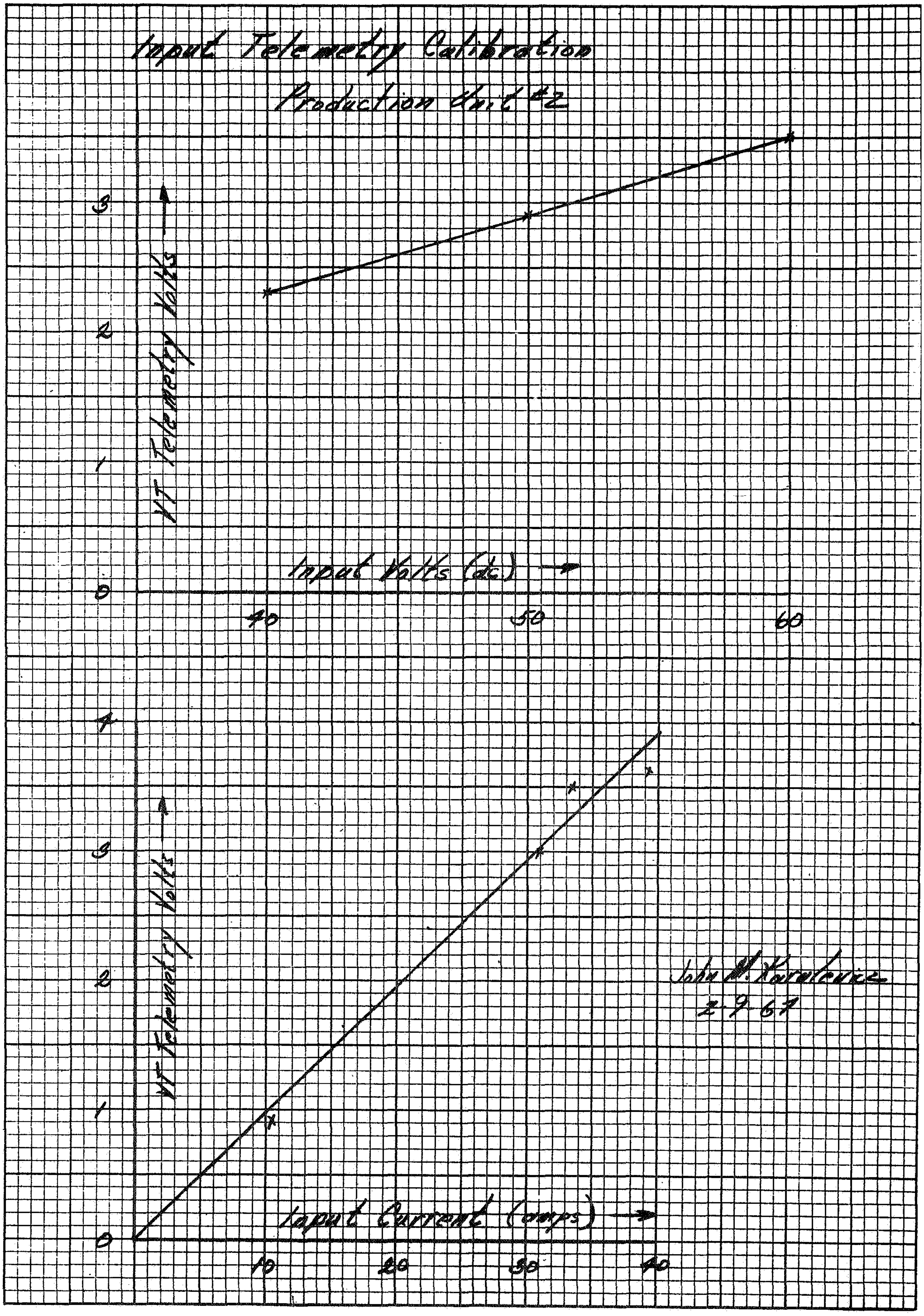

SCREEN VOLTAGE TELEMETRY TRANSFER
CHARACTERISTIC — V5 TELEMETRY VERSUS
ACTUAL SCREEN KV. 9-2-66 P Corey
SCREEN VOLTAGE (V5) TELEMETRY OUTPUT, DC VOLTS
0
1
2
3
4
5
SCREEN VOLTAGE, DC KILOVOLTS

FIG. 24



SCREEN CURRENT TELEMETRY
TRANSFER CHARACTERISTIC - I.5
TELEMETRY VERSUS ACTUAL SCREEN MA.
SCREEN CURRENT, D C MILLIAMPERES.
50
100
150
200
250
300
I.5 TELEMETRY OUTPUT, DC VOLTS

FIG. 25 3



Input Telemetry Calibration
Production Unit #2
VT Telemetry Volts
Input Volts (dc.)
0
1
2
3
40
50
60
VT Telemetry Volts
Input Current (amps)
0
1
2
3
4
10
20
30
40
John M. Karwlewicz
2-9-67

Fig. 26

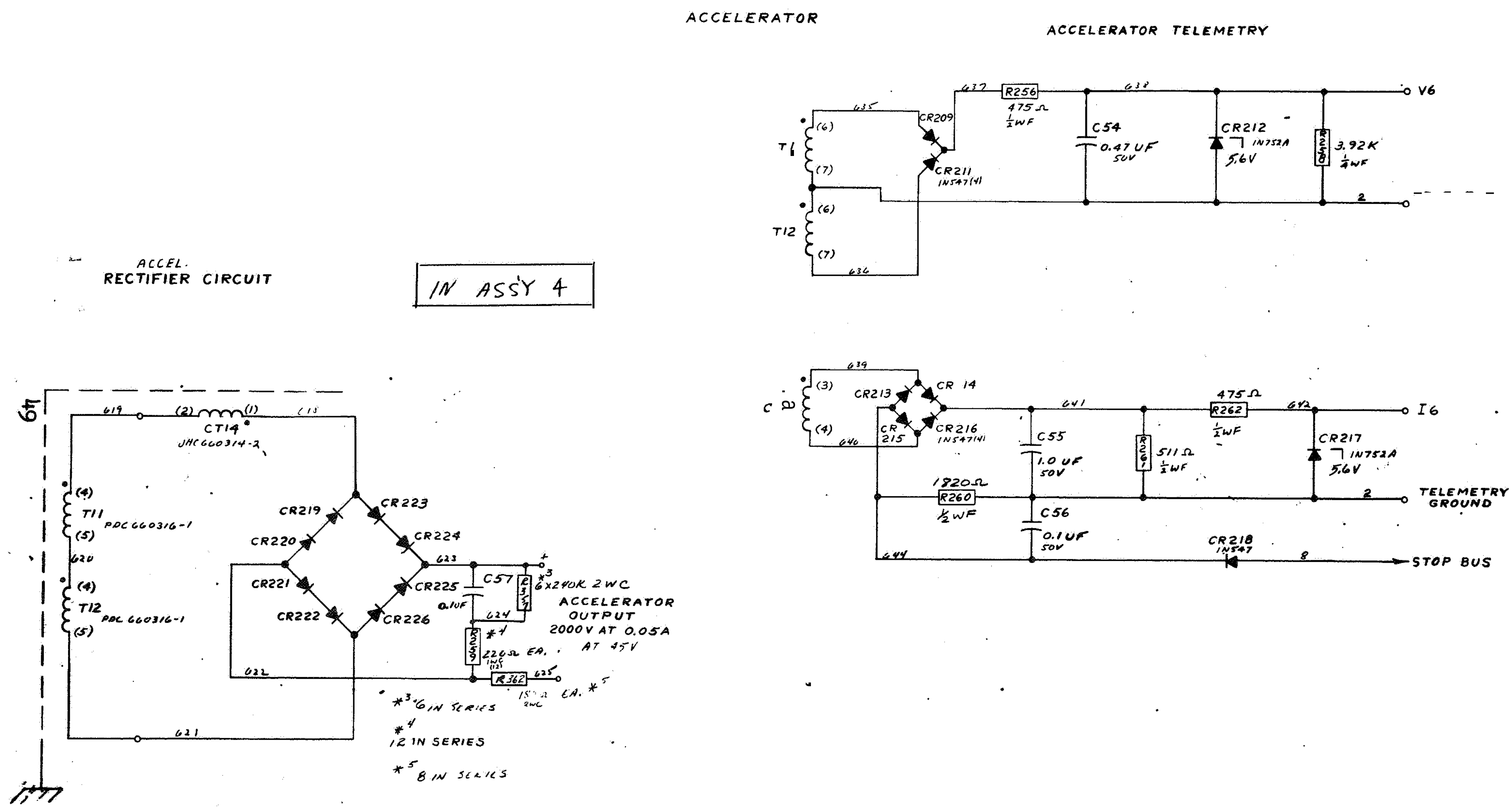

ACCELERATOR
ACCELERATOR TELEMETRY
ACCEL.
RECTIFIER CIRCUIT
IN ASS'Y 4
T11
T12
CR209
CR211
1N547(4)
R256
475Ω
½WF
C54
0.47 UF
50V
CR212
1N752A
5.6V
3.92K
¼WF
V6
CR 14
CR213
CR 215
CR216
1N547(4)
C55
1.0 UF
50V
R261
511Ω
½WF
475Ω
R262
½WF
CR217
1N752A
5.6V
I6
1820Ω
R260
½WF
C56
0.1UF
50V
TELEMETRY
GROUND
CR218
1N547
STOP BUS
CT14
JHC660314-2
T11 PDC660316-1
T12 PDC660316-1
CR219
CR220
CR221
CR222
CR223
CR224
CR225
CR226
C57
0.1UF
6x240K 2WC
ACCELERATOR
OUTPUT
2000V AT 0.05A
AT 45V
226Ω EA.
R362
15Ω EA.
*3 6 IN SERIES
*4 12 IN SERIES
*5 8 IN SERIES

FIG. 27

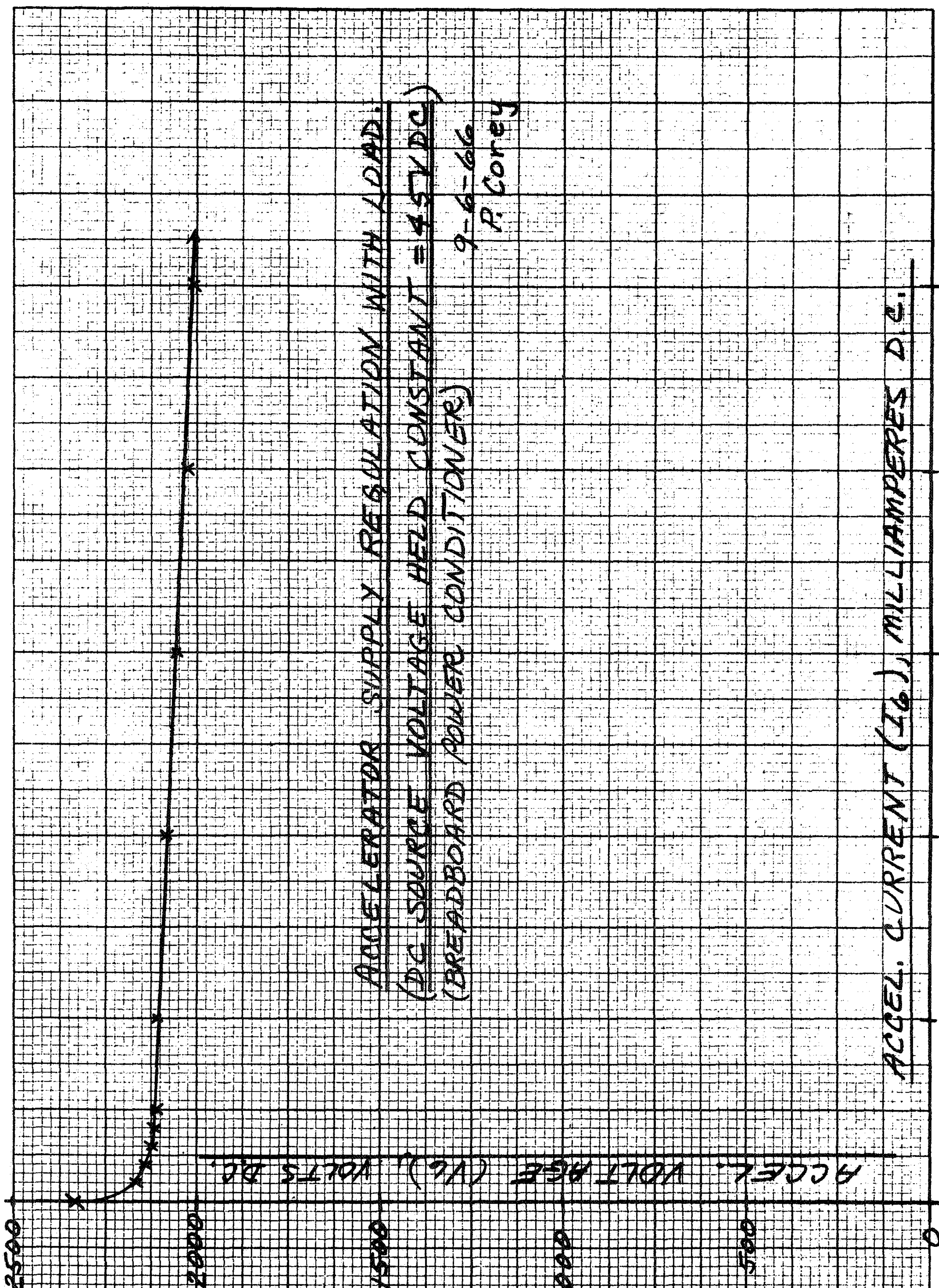

ACCELERATOR SUPPLY REGULATION WITH LOAD.
(DC SOURCE VOLTAGE HELD CONSTANT = 45 V DC)
(BREADBOARD POWER CONDITIONER)
9-6-66
P. Corey
ACCEL. CURRENT (IG), MILLIAMPERES D.C.
ACCEL. VOLTAGE (VG), VOLTS DC.
0
10
20
30
40
50
2500
2000
1500
1000
500
0

FIGURE 28

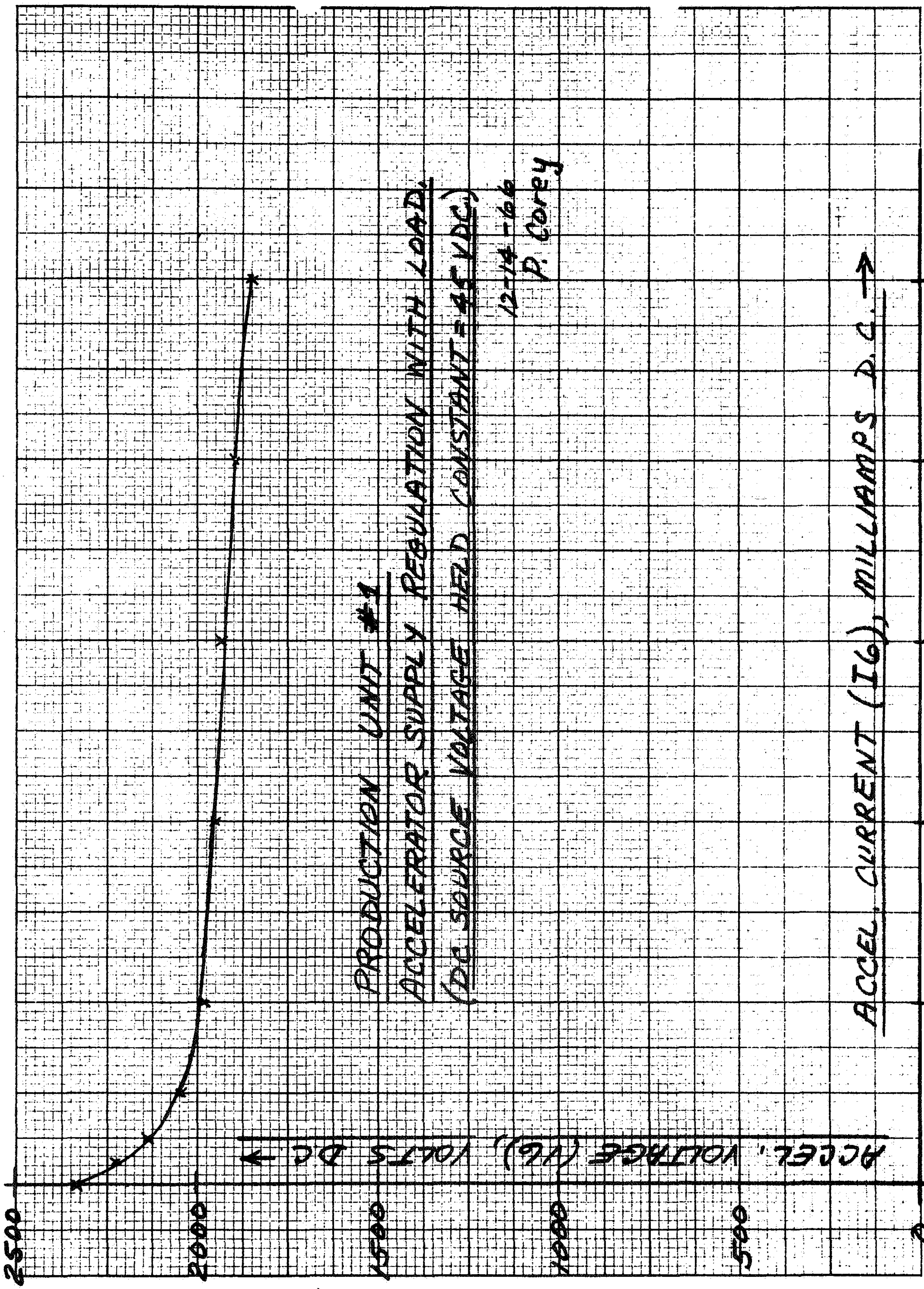
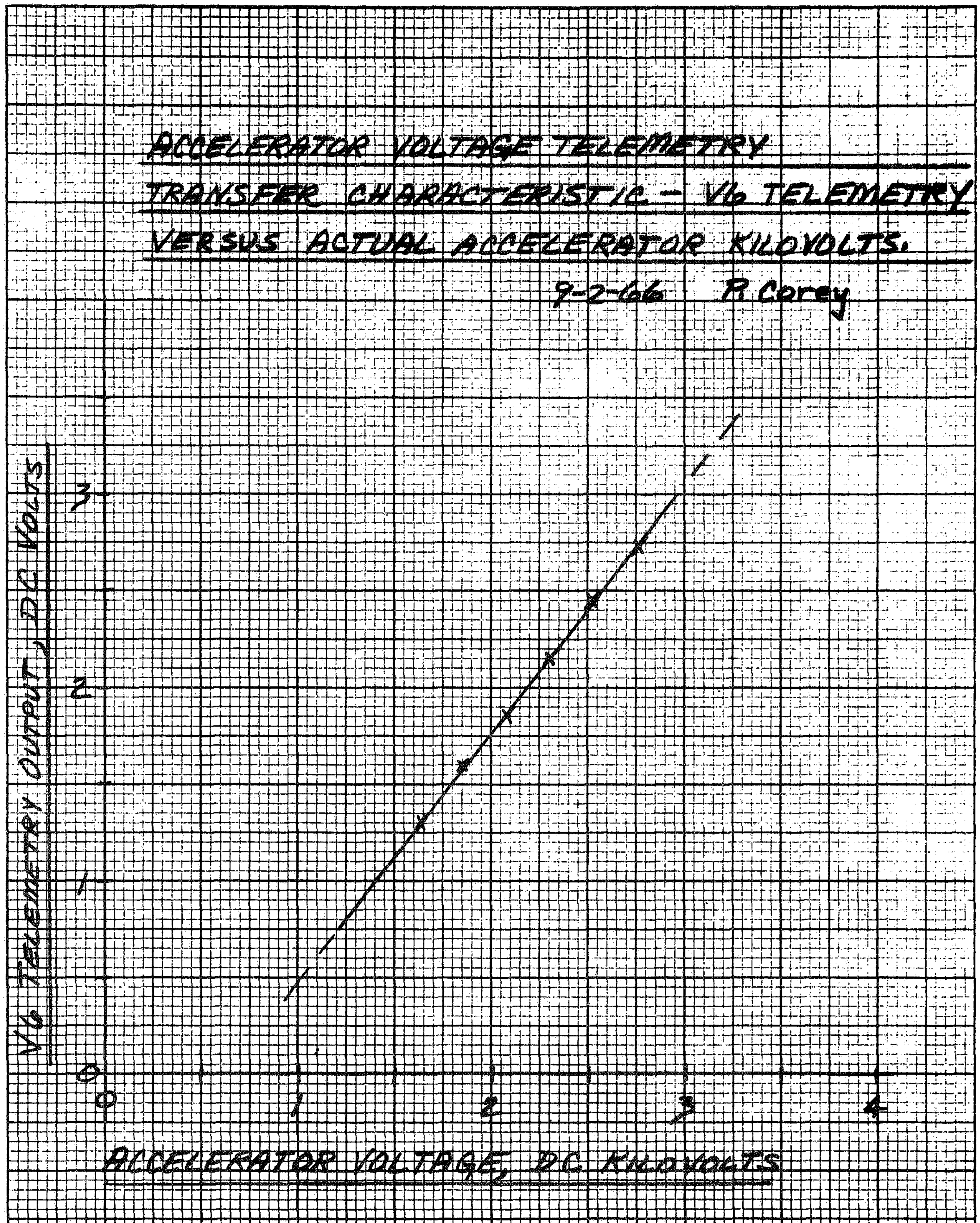

PRODUCTION UNIT #1
ACCELERATOR SUPPLY REGULATION WITH LOAD.
(DC SOURCE VOLTAGE HELD CONSTANT = 45 VDC)
12-14-66
P. Corey
ACCEL. CURRENT (IG), MILLIAMPS D.C.
ACCEL. VOLTAGE (VG), VOLTS DC
0
10
20
30
40
50
0
500
1000
1500
2000
2500

FIG 29



ACCELERATOR VOLTAGE TELEMETRY
TRANSFER CHARACTERISTIC - V6 TELEMETRY
VERSUS ACTUAL ACCELERATOR KILOVOLTS.
9-2-66 R Corey
V6 TELEMETRY OUTPUT, DC VOLTS
3
2
1
0
0
1
2
3
4
ACCELERATOR VOLTAGE, DC KILOVOLTS

FIG. 30

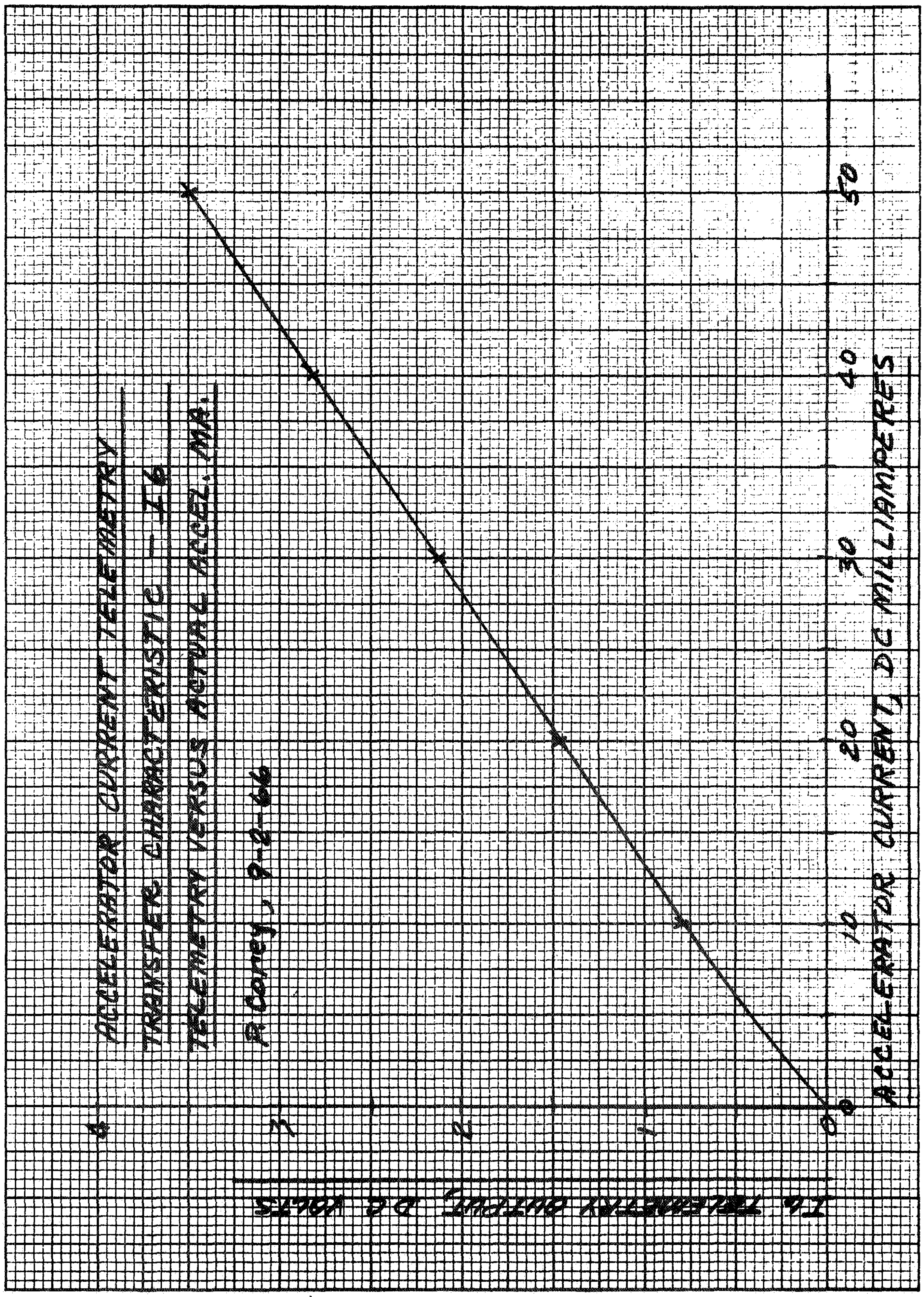

ACCELERATOR CURRENT TELEMETRY
TRANSFER CHARACTERISTIC - I6
TELEMETRY VERSUS ACTUAL ACCEL. MA.
P. Comey, 9-2-66
ACCELERATOR CURRENT, DC MILLIAMPERES
0
10
20
30
40
50
I6 TELEMETRY OUTPUT, DC VOLTS
0
1
2
3
4

FIG. 31

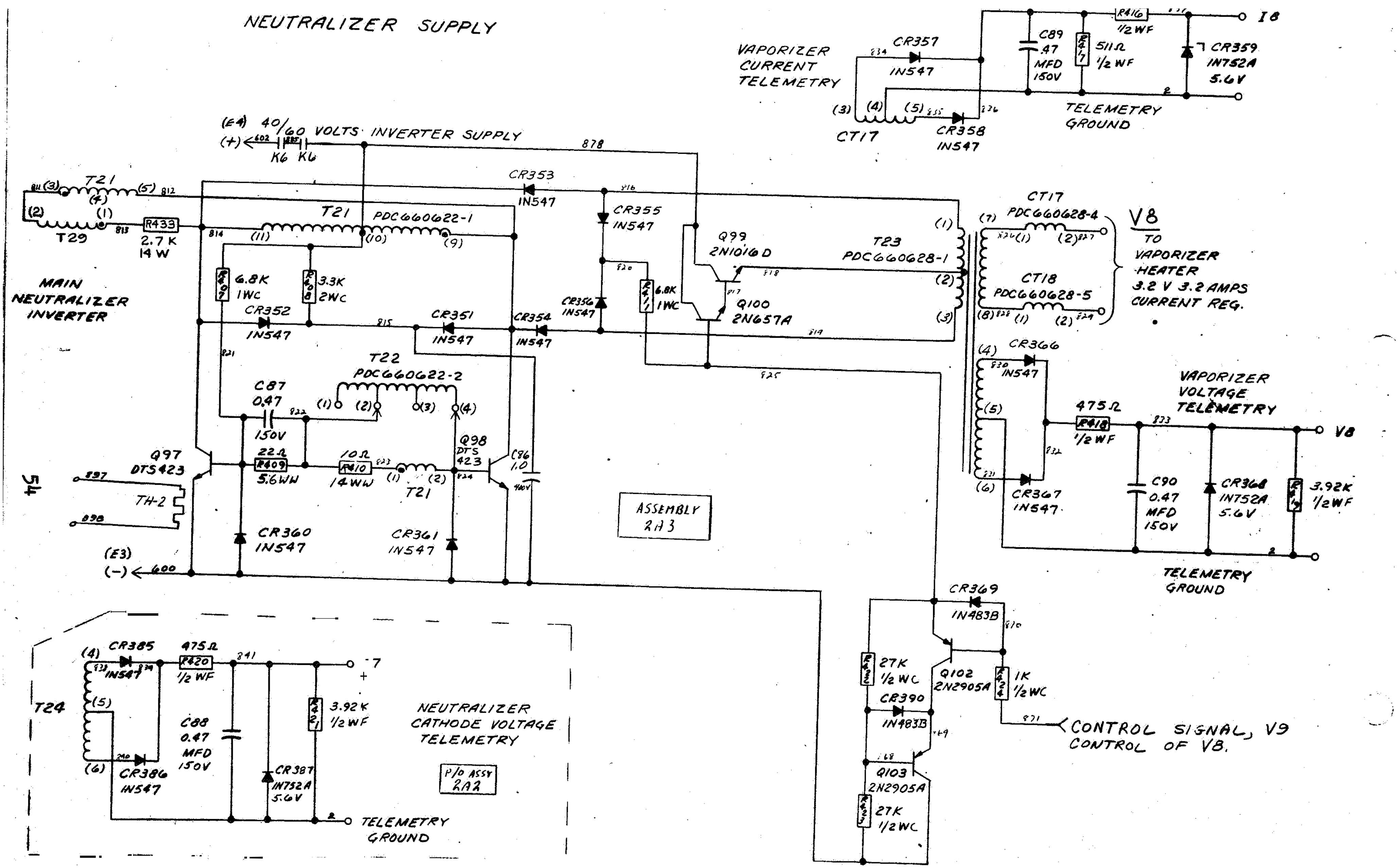

NEUTRALIZER SUPPLY
VAPORIZER CURRENT TELEMETRY
CR357 1N547
C89 .47 MFD 150V
R416 1/2 WF
511Ω 1/2 WF
I8
CR359 1N752A 5.6V
TELEMETRY GROUND
CT17
CR358 1N547
(E4) 40/60 VOLTS INVERTER SUPPLY
(+)
K6 K6
878
T21
T29
R433 2.7 K 14 W
CR353 1N547
CR355 1N547
T21 PDC660622-1
MAIN NEUTRALIZER INVERTER
6.8K 1WC
3.3K 2WC
CR352 1N547
CR351 1N547
CR354 1N547
CR356 1N547
6.8K 1WC
Q99 2N1016D
Q100 2N657A
T23 PDC660628-1
CT17 PDC660628-4
CT18 PDC660628-5
V8 TO VAPORIZER HEATER 3.2 V 3.2 AMPS CURRENT REG.
T22 PDC660622-2
C87 0.47 150V
22Ω R409 5.6WW
10Ω R410 14WW
Q97 DTS423
Q98 DTS 423
C96 1.0
TH-2
CR360 1N547
CR361 1N547
(E3) (-)
ASSEMBLY 2A3
CR366 1N547
CR367 1N547
VAPORIZER VOLTAGE TELEMETRY
475Ω R418 1/2 WF
V8
C90 0.47 MFD 150V
CR368 1N752A 5.6V
3.92K 1/2WF
TELEMETRY GROUND
CR369 1N483B
27K 1/2 WC
Q102 2N2905A
1K 1/2WC
CR390 1N483B
Q103 2N2905A
27K 1/2WC
CONTROL SIGNAL, V9 CONTROL OF V8.
T24
CR385 1N547
475Ω R420 1/2 WF
C88 0.47 MFD 150V
3.92K 1/2WF
CR386 1N547
CR387 1N752A 5.6V
NEUTRALIZER CATHODE VOLTAGE TELEMETRY
P/O ASSY 2A2
TELEMETRY GROUND

FIG 32

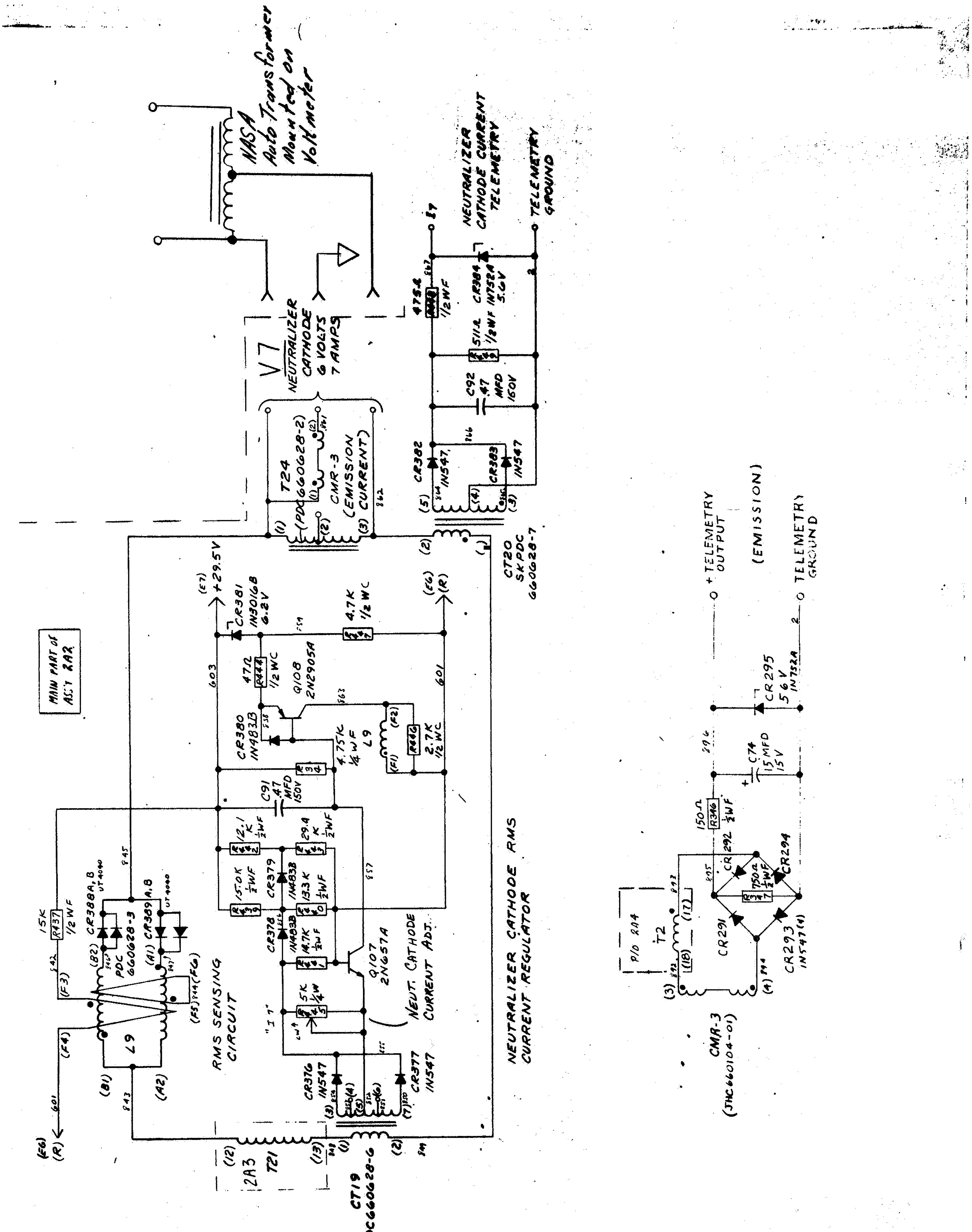
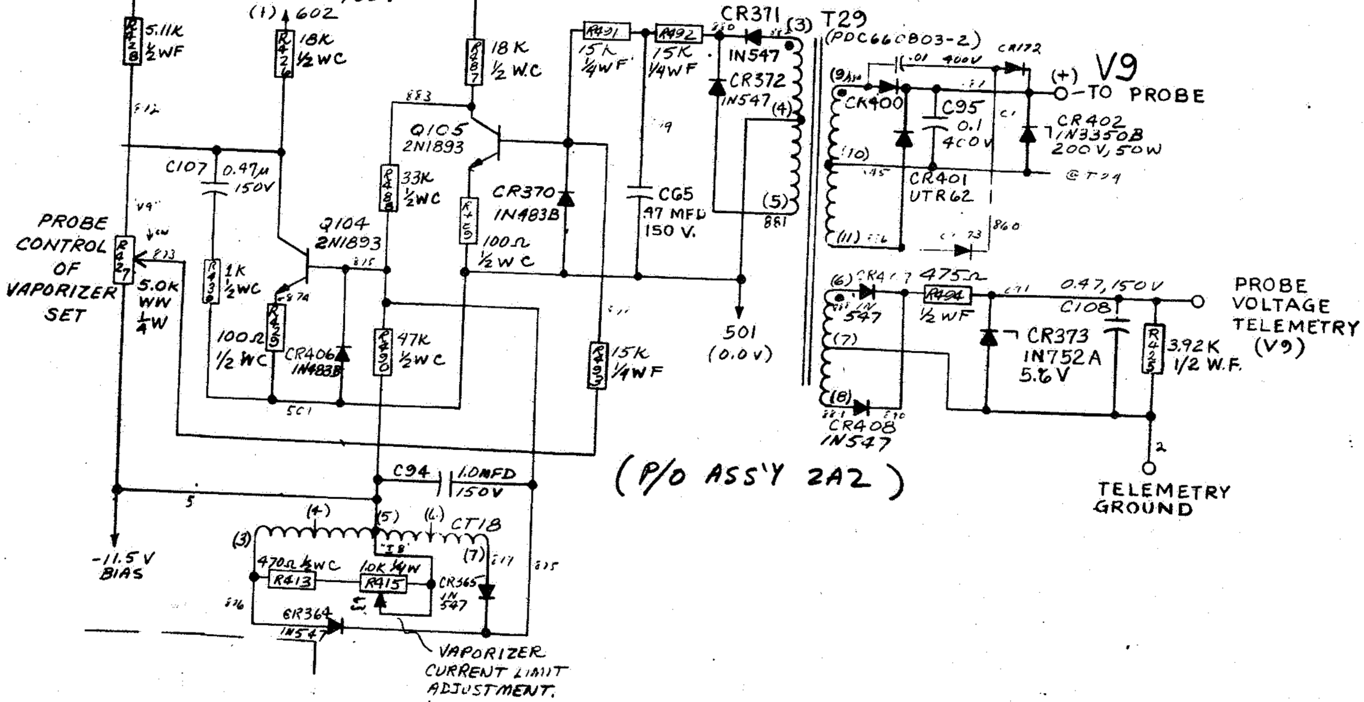

NASA Auto Transformer Mounted on Voltmeter
NEUTRALIZER CATHODE CURRENT TELEMETRY
TELEMETRY GROUND
V7 NEUTRALIZER CATHODE 6 VOLTS 7 AMPS
T24 (PDC660628-2)
CMR-3 (EMISSION CURRENT)
475Ω 1/2WF
CR384 IN752A 5.6V
511Ω 1/8WF
C92 .47 MFD 160V
CR382 IN547
CR383 IN547
CT20 SKPDC 660628-7
+29.5V
CR381 IN3016B 6.2V
4.7K 1/2WC
47Ω 1/2WC
Q108 2N2905A
CR380 IN483B
4.75K 1/4WF
L9
2.7K 1/2WC
C91 .47 MFD 150V
12.1K 1/2WF
29.4K 1/2WF
150.0K 1/2WF
CR379 IN483B
13.3K 1/2WF
CR378 IN483B
14.7K 1/2WF
5K 1/4W
Q107 2N657A
NEUT. CATHODE CURRENT ADJ.
NEUTRALIZER CATHODE RMS CURRENT REGULATOR
MAIN PART OF ASS'Y 2A2
15K R437 1/2WF
CR388A,B UT4040
CR389A,B UT4040
PDC 660628-3
L9
RMS SENSING CIRCUIT
CR376 IN547
CR377 IN547
2A3 T21
CT19 PDC660628-6
+ TELEMETRY OUTPUT
(EMISSION)
TELEMETRY GROUND
CR295 5.6V IN752A
C74 15MFD 15V
150Ω R346 1/2WF
CR292
CR294
750Ω 1/2WF
CR291
CR293 IN547(4)
P/O 2A4
T2
CMR-3 (JHC660104-01)

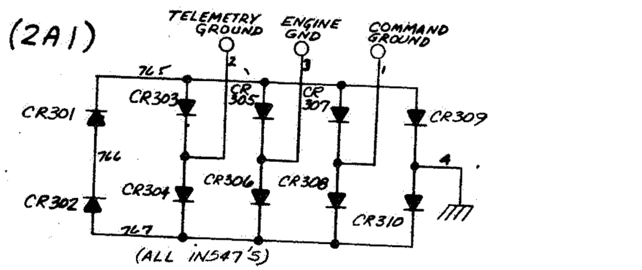
FIG 33

NEUT. SUPPLY, CONT'D:



(P/O ASS'Y 2A2)

(2A1)



GROUND INTERCONNETION DIODE MATRIX

FIG. 34

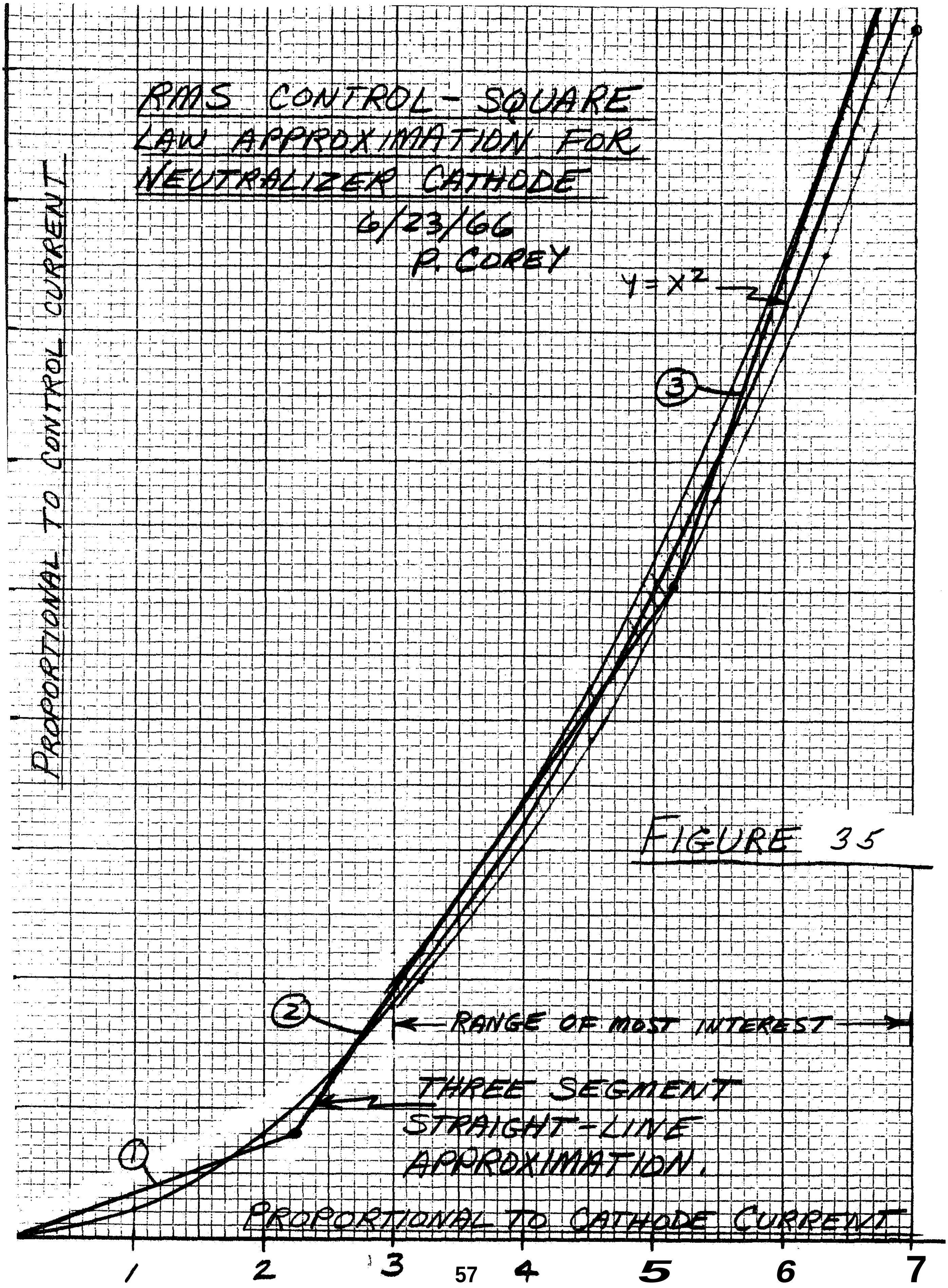
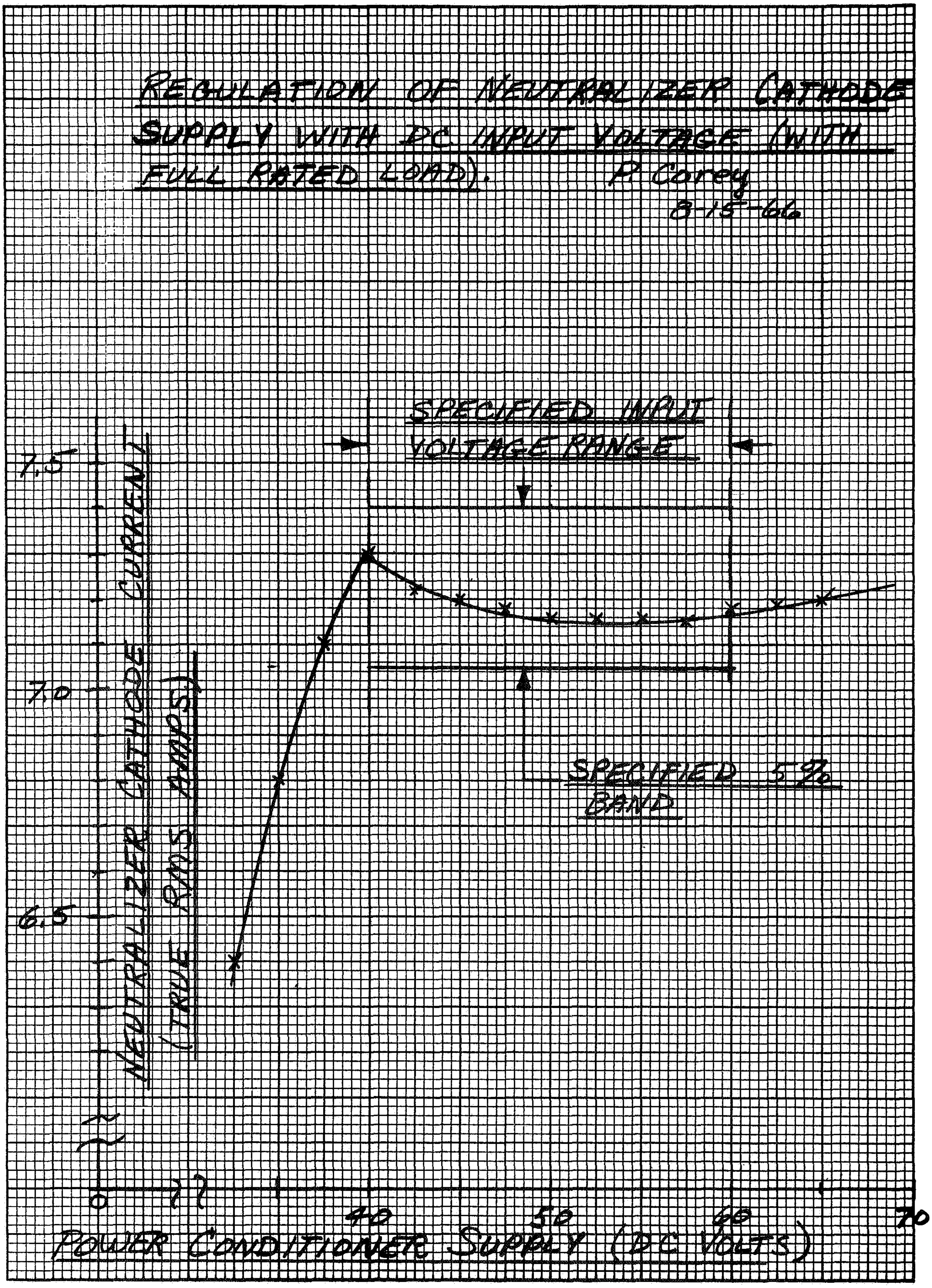
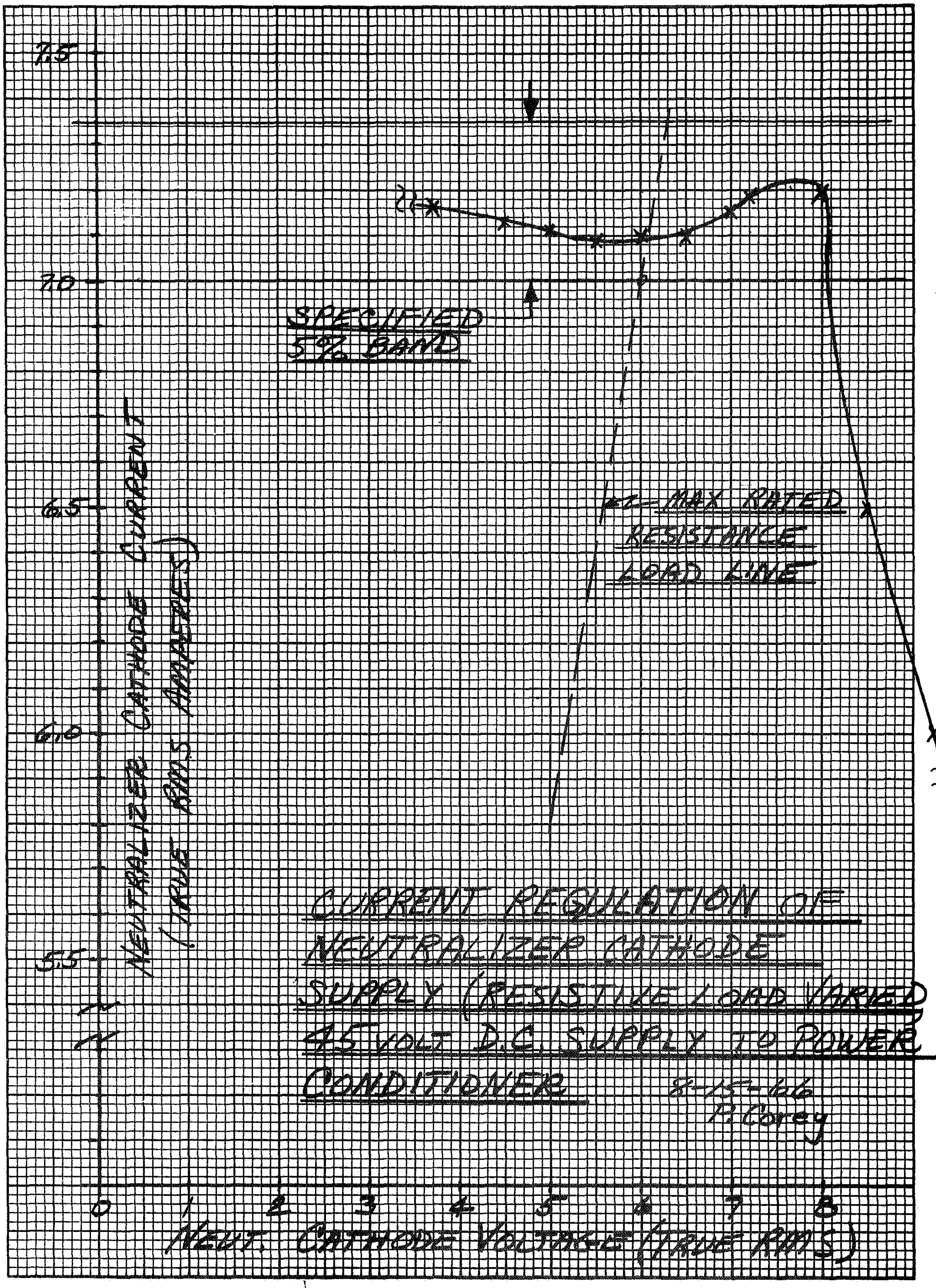

RMS CONTROL - SQUARE
LAW APPROXIMATION FOR
NEUTRALIZER CATHODE
6/23/66
P. COREY
Y = X²
3
2
1
RANGE OF MOST INTEREST
THREE SEGMENT
STRAIGHT-LINE
APPROXIMATION.
PROPORTIONAL TO CONTROL CURRENT
PROPORTIONAL TO CATHODE CURRENT
1
2
3
4
5
6
7

FIGURE 35



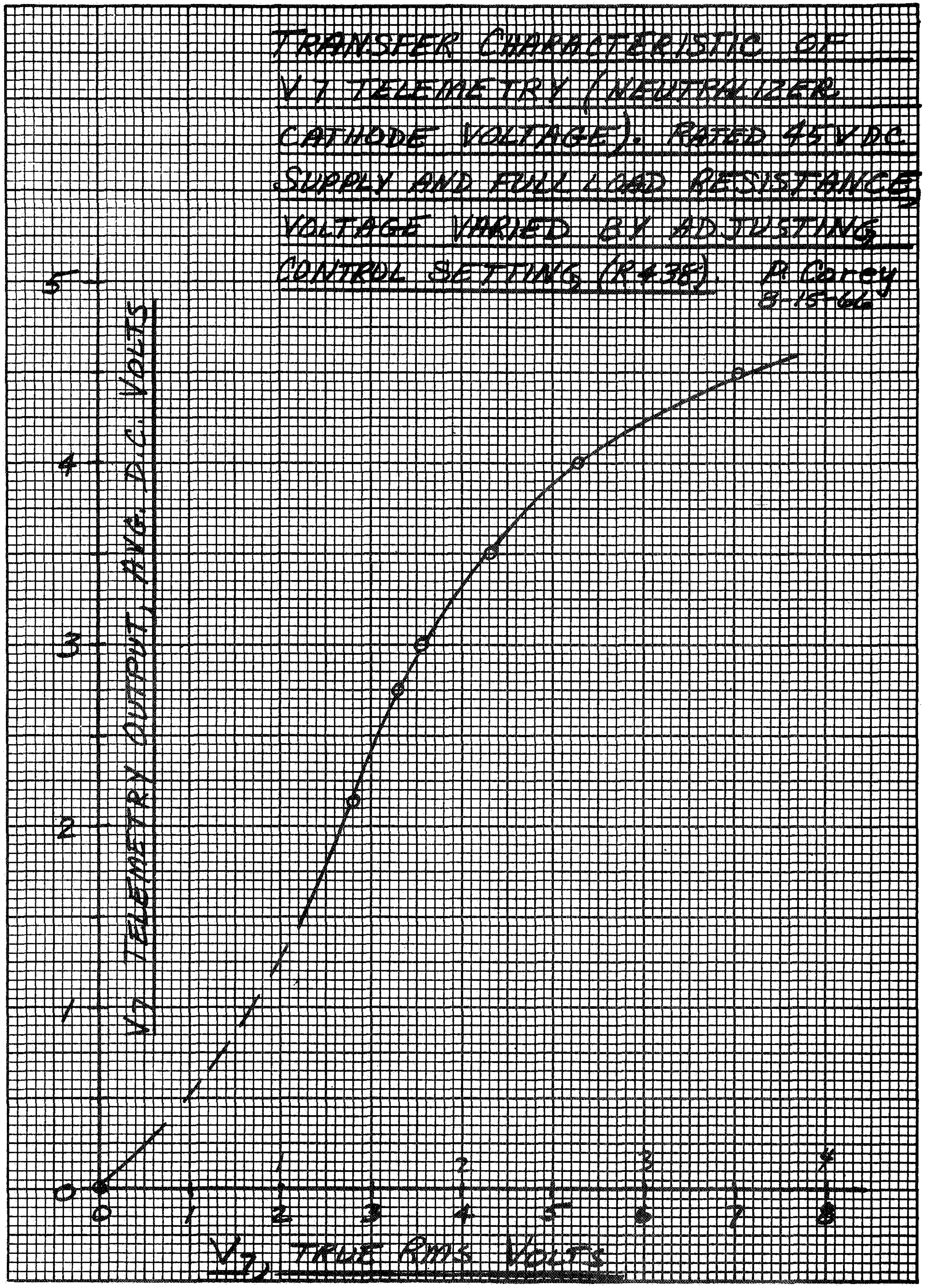
REGULATION OF NEUTRALIZER CATHODE SUPPLY WITH DC INPUT VOLTAGE (WITH FULL RATED LOAD).
R. Corey
8-15-66
SPECIFIED INPUT VOLTAGE RANGE
SPECIFIED 5% BAND
NEUTRALIZER CATHODE CURRENT
(TRUE RMS AMPS)
7.5
7.0
6.5
0
40
50
60
70
POWER CONDITIONER SUPPLY (DC VOLTS)

FIG. 36



7.5
7.0
6.5
6.0
5.5
0
1
2
3
4
5
6
7
8
NEUTRALIZER CATHODE CURRENT
(TRUE RMS AMPERES)
NEUT. CATHODE VOLTAGE (TRUE RMS)
SPECIFIED
5% BAND
MAX RATED
RESISTANCE
LOAD LINE
CURRENT REGULATION OF
NEUTRALIZER CATHODE
SUPPLY (RESISTIVE LOAD VARIED
45 VOLT D.C. SUPPLY TO POWER
CONDITIONER
8-15-66
R. Corey

FIG. 37.



TRANSFER CHARACTERISTIC OF
V7 TELEMETRY (NEUTRALIZER
CATHODE VOLTAGE). RATED 45 VDC
SUPPLY AND FULL LOAD RESISTANCE;
VOLTAGE VARIED BY ADJUSTING
CONTROL SETTING (R438).
P. Carey
8-15-66
V7 TELEMETRY OUTPUT, AVG. D.C. VOLTS
V7, TRUE RMS VOLTS
0
1
2
3
4
5
6
7
8

FIG. 38

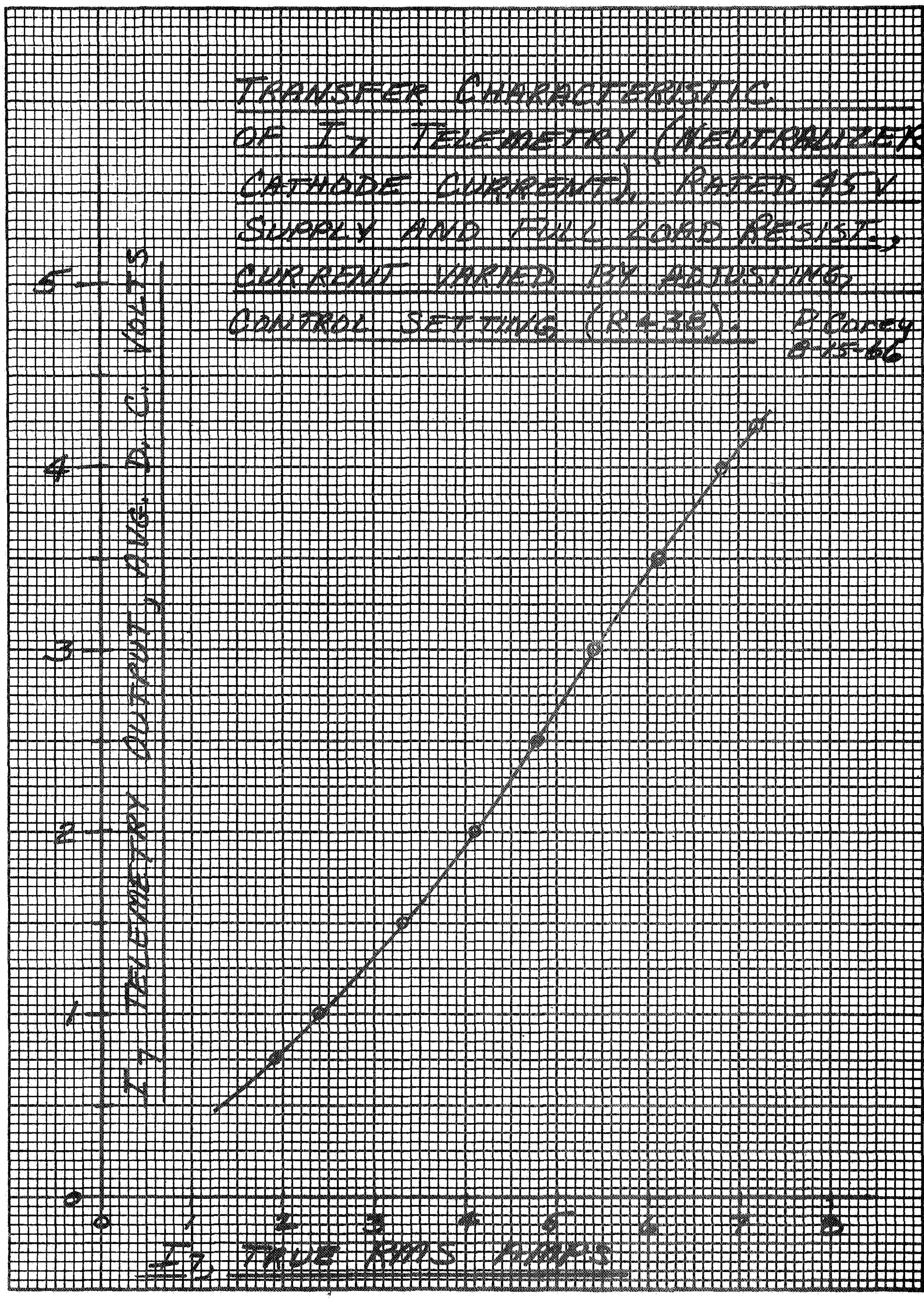
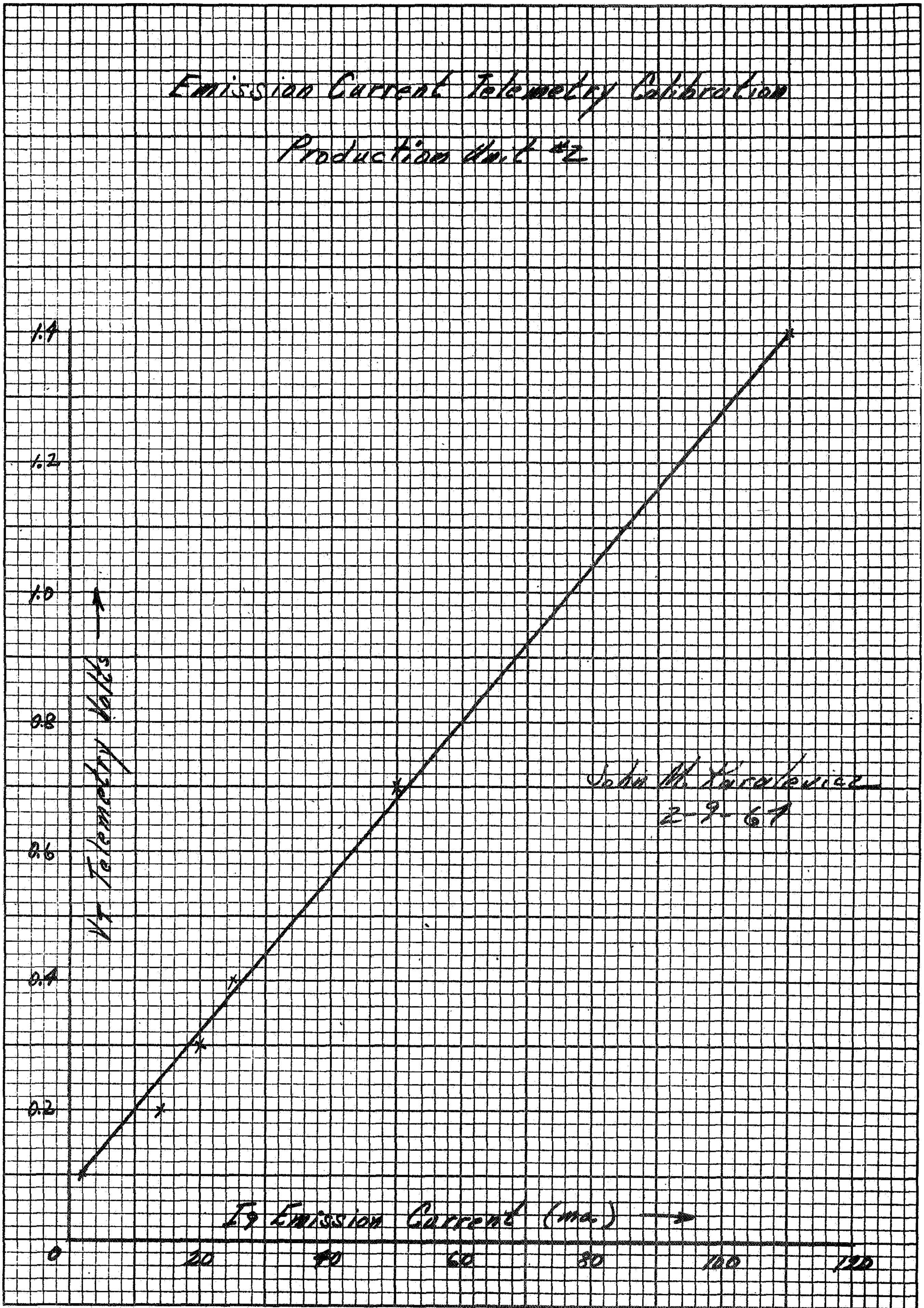

TRANSFER CHARACTERISTIC
OF I7 TELEMETRY (NEUTRALIZER
CATHODE CURRENT), RATED 45 V
SUPPLY AND FULL LOAD RESIST.,
CURRENT VARIED BY ADJUSTING
CONTROL SETTING (R438).
P. Corey
8-15-66
I7 TELEMETRY OUTPUT, AVG. D. C. VOLTS
0
1
2
3
4
5
0
1
2
3
4
5
6
7
8
I7 TRUE RMS AMPS

FIG. 39



Emission Current Telemetry Calibration
Production Unit #2
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
20
40
60
80
100
120
V_T Telemetry Volts
I_e Emission Current (ma.)
John M. Karalevicz
2-9-67

Fig. 40

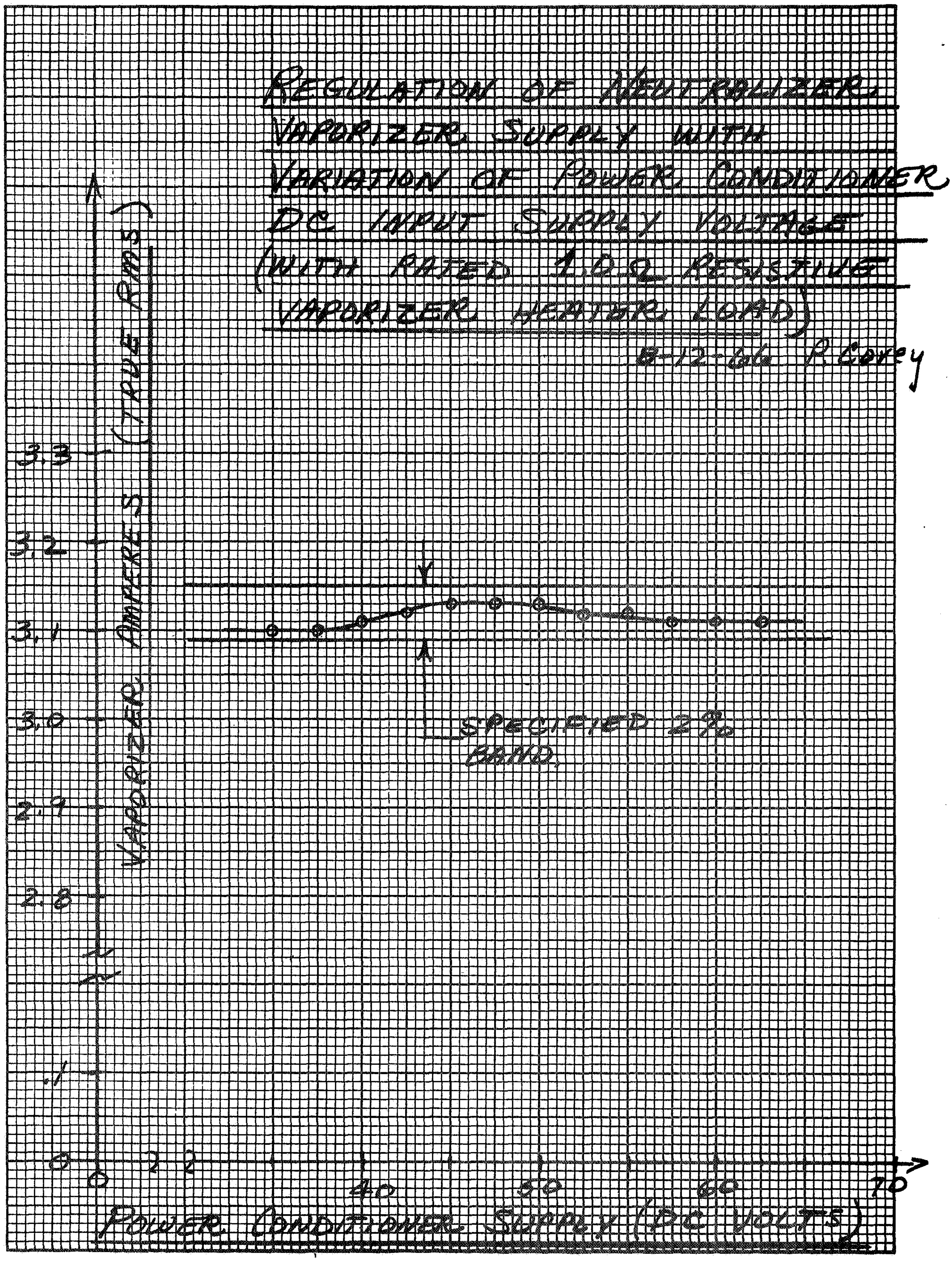

REGULATION OF NEUTRALIZER VAPORIZER SUPPLY WITH VARIATION OF POWER CONDITIONER DC INPUT SUPPLY VOLTAGE (WITH RATED 1.0 Ω RESISTIVE VAPORIZER HEATER LOAD)
8-12-66 R Corey
VAPORIZER AMPERES (TRUE RMS)
3.3
3.2
3.1
3.0
2.9
2.8
.1
0
SPECIFIED 2% BAND.
0
2
2
40
50
60
70
POWER CONDITIONER SUPPLY (DC VOLTS)

FIG. 41

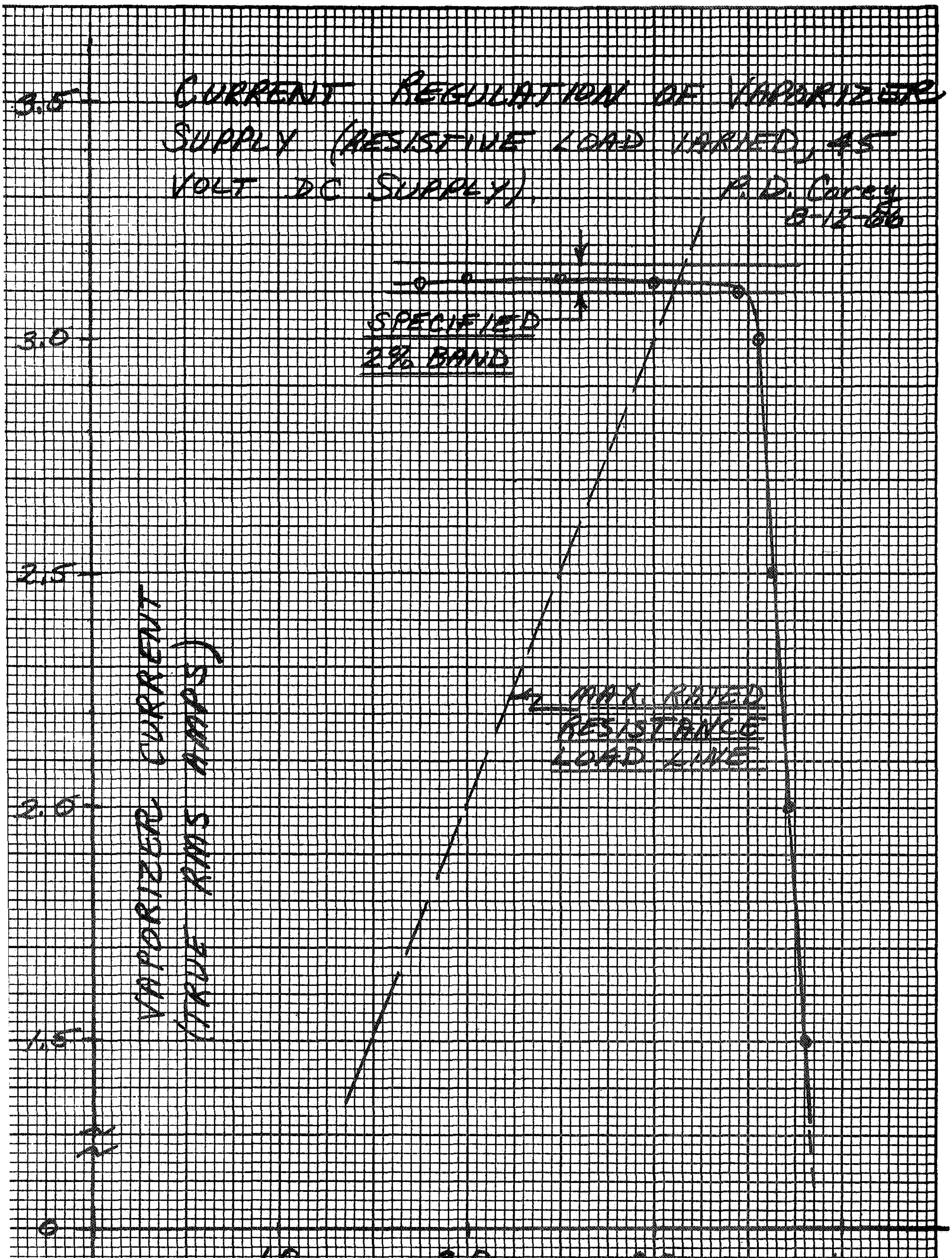

CURRENT REGULATION OF VAPORIZER SUPPLY (RESISTIVE LOAD VARIED, 45 VOLT DC SUPPLY).
R.D. Corey
8-12-86
SPECIFIED 2% BAND
MAX. RATED RESISTANCE LOAD LINE
VAPORIZER CURRENT (TRUE RMS AMPS)
VAPORIZER AC VOLTS (TRUE RMS)
3.5
3.0
2.5
2.0
1.5
0
0
1.0
2.0
3.0
4.0

Fig. 42

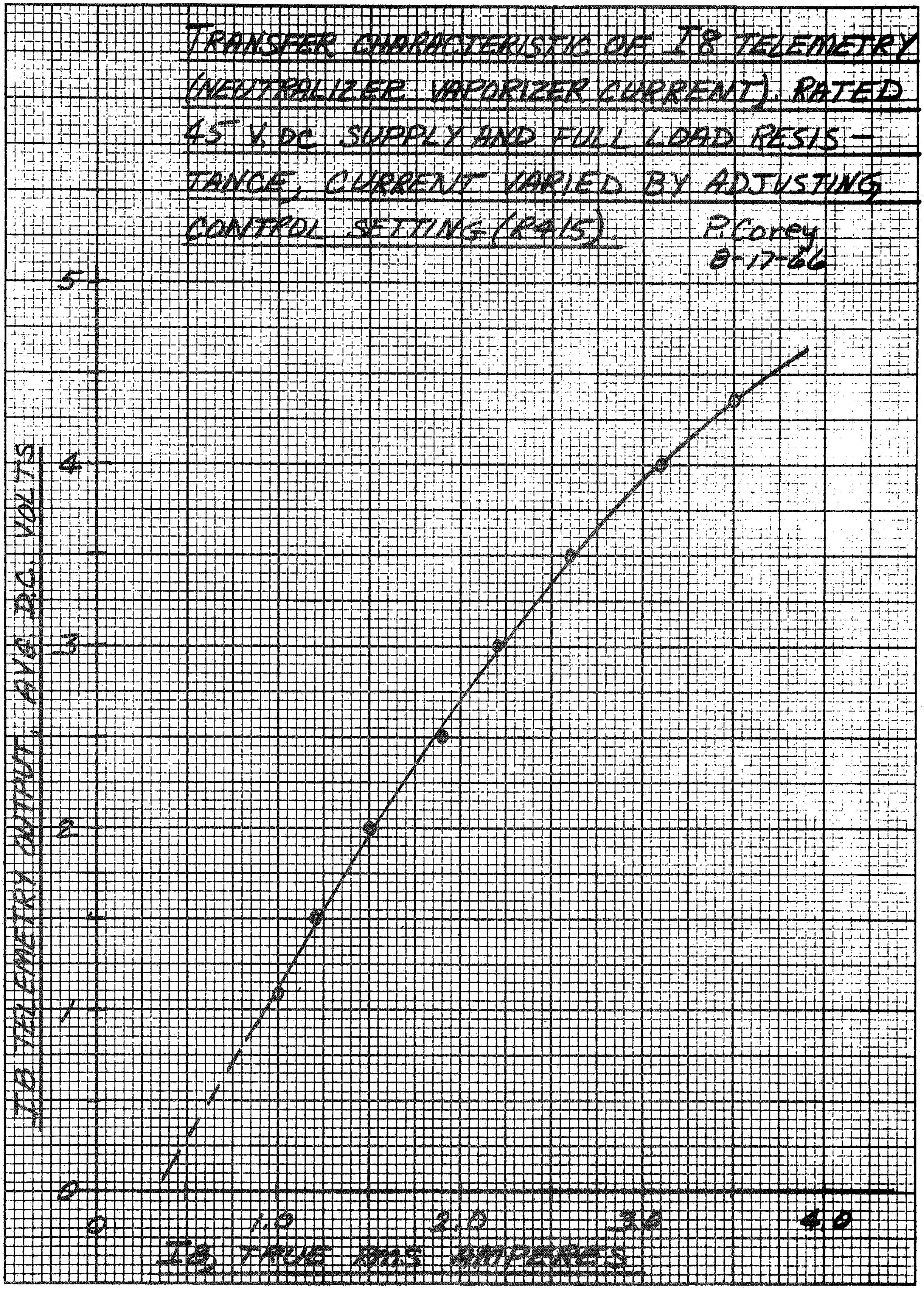
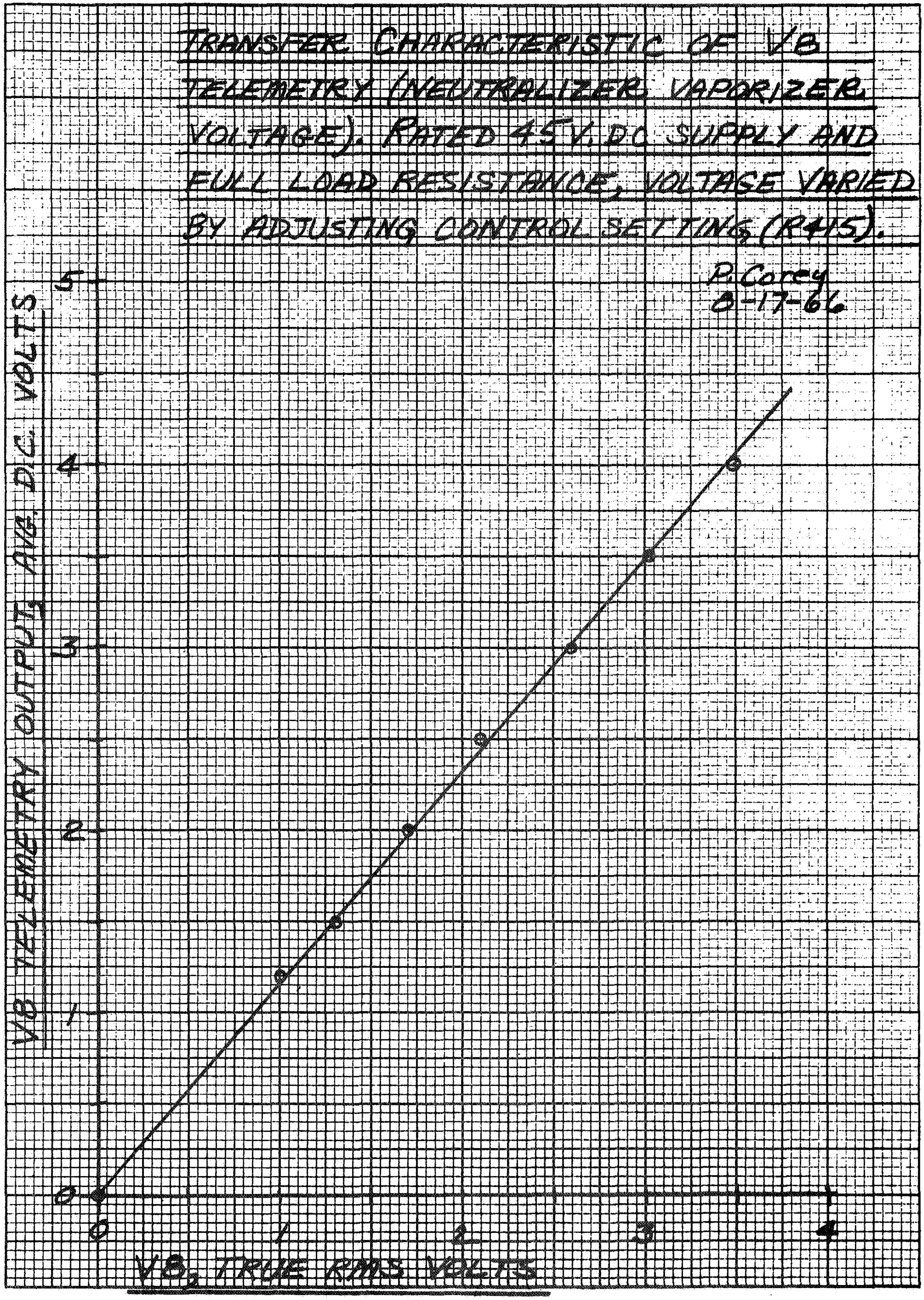

TRANSFER CHARACTERISTIC OF I8 TELEMETRY (NEUTRALIZER VAPORIZER CURRENT) RATED 45 V. DC SUPPLY AND FULL LOAD RESIS-TANCE, CURRENT VARIED BY ADJUSTING CONTROL SETTING (R415).
P. Corey
8-17-66
I8 TELEMETRY OUTPUT, AVG. D.C. VOLTS
I8, TRUE RMS AMPERES
0
1
2
3
4
5
0
1.0
2.0
3.0
4.0

FIG. 43



TRANSFER CHARACTERISTIC OF VB TELEMETRY (NEUTRALIZER VAPORIZER VOLTAGE). RATED 45 V. DC SUPPLY AND FULL LOAD RESISTANCE, VOLTAGE VARIED BY ADJUSTING CONTROL SETTING (R415).
P. Corey
8-17-66
VB TELEMETRY OUTPUT, AVG. D.C. VOLTS
VB, TRUE RMS VOLTS
0
1
2
3
4
5

FIG. 44

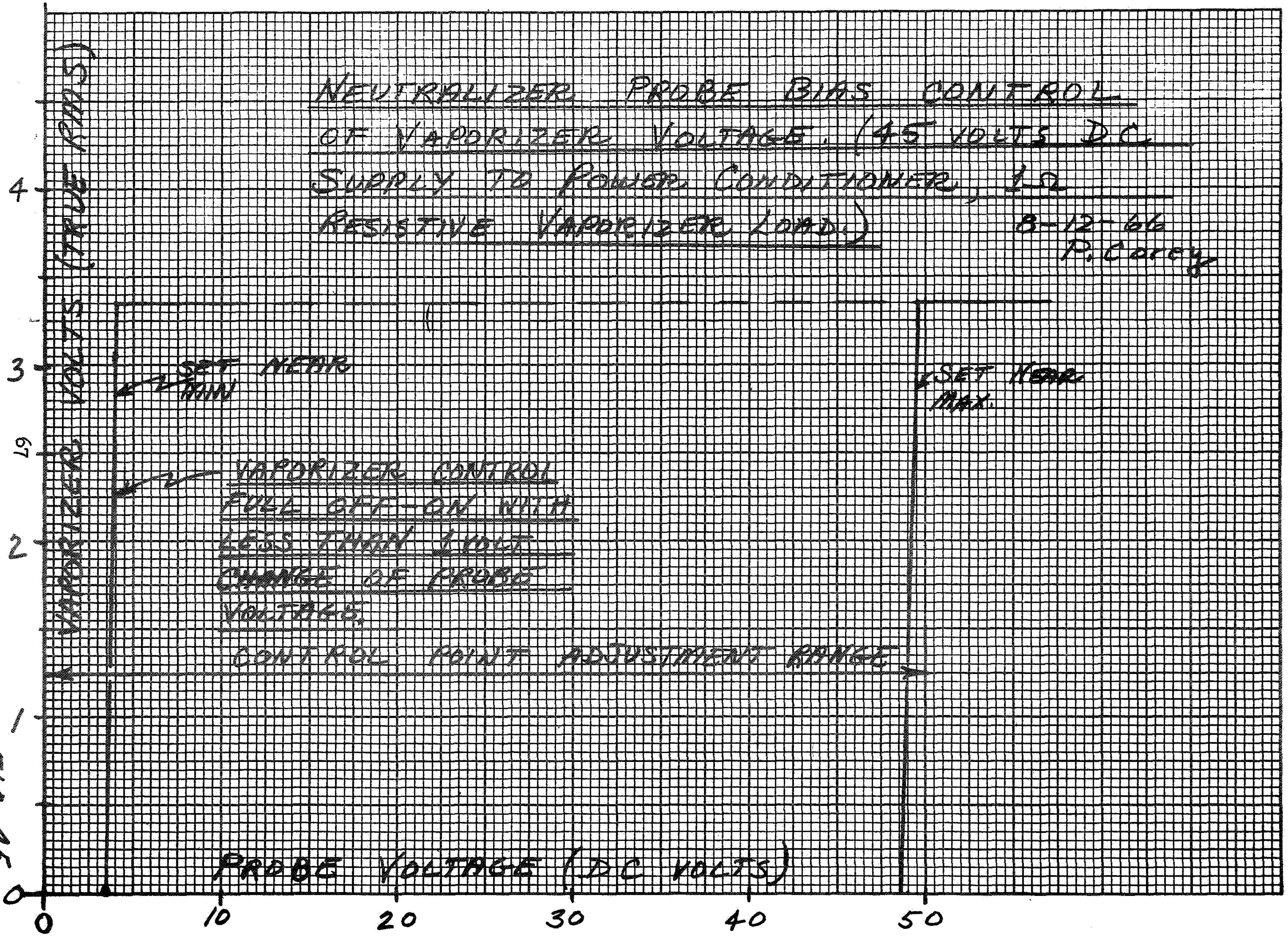

NEUTRALIZER PROBE BIAS CONTROL
OF VAPORIZER VOLTAGE. (45 VOLTS DC
SUPPLY TO POWER CONDITIONER, 1Ω
RESISTIVE VAPORIZER LOAD.)
8-12-66
P. Corey
SET NEAR MIN
SET NEAR MAX.
VAPORIZER CONTROL
FULL OFF-ON WITH
LESS THAN 1 VOLT
CHANGE OF PROBE
VOLTAGE.
CONTROL POINT ADJUSTMENT RANGE
VAPORIZER VOLTS (TRUE RMS)
PROBE VOLTAGE (DC VOLTS)
0
1
2
3
4
0
10
20
30
40
50

FIG 45

67

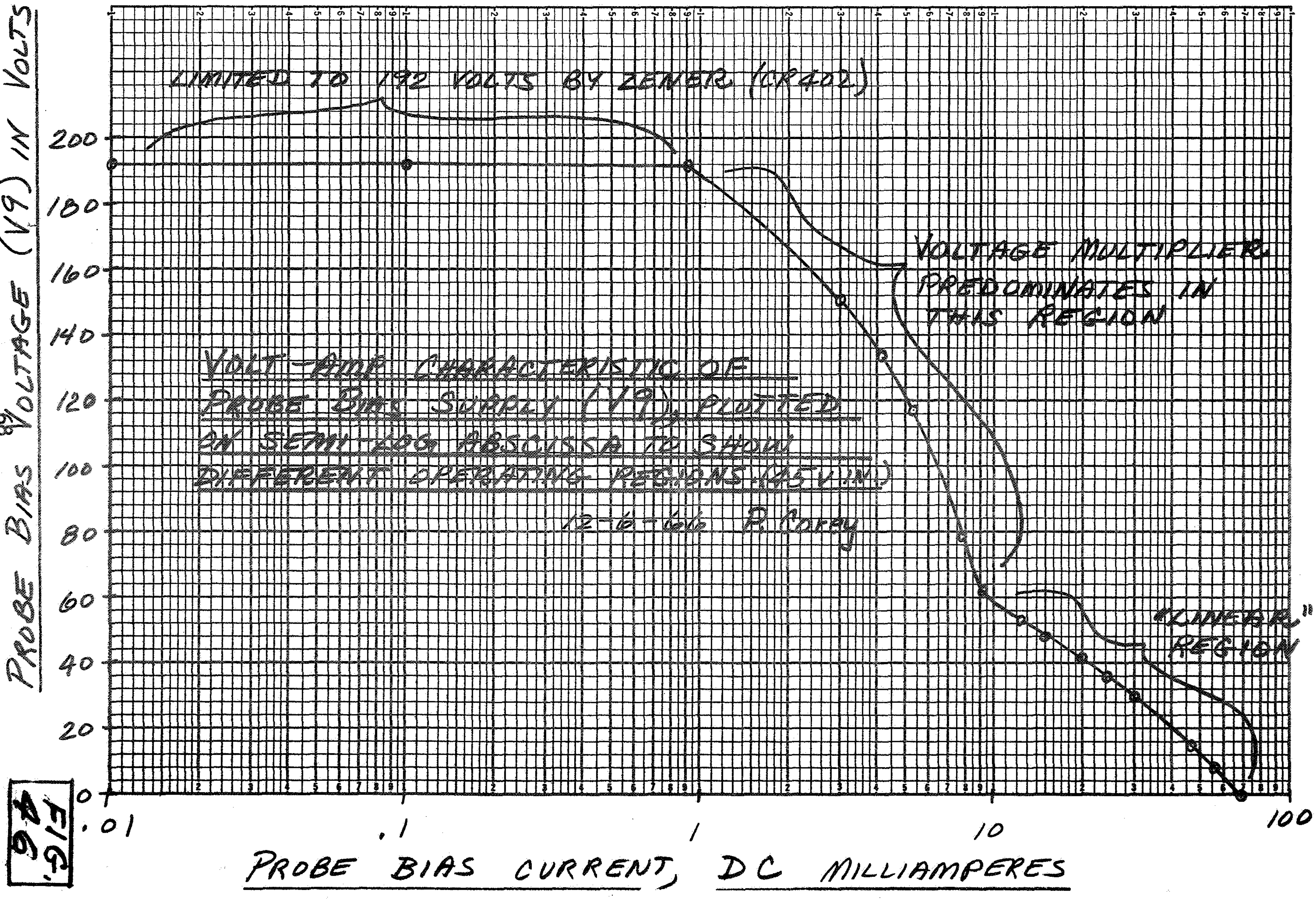
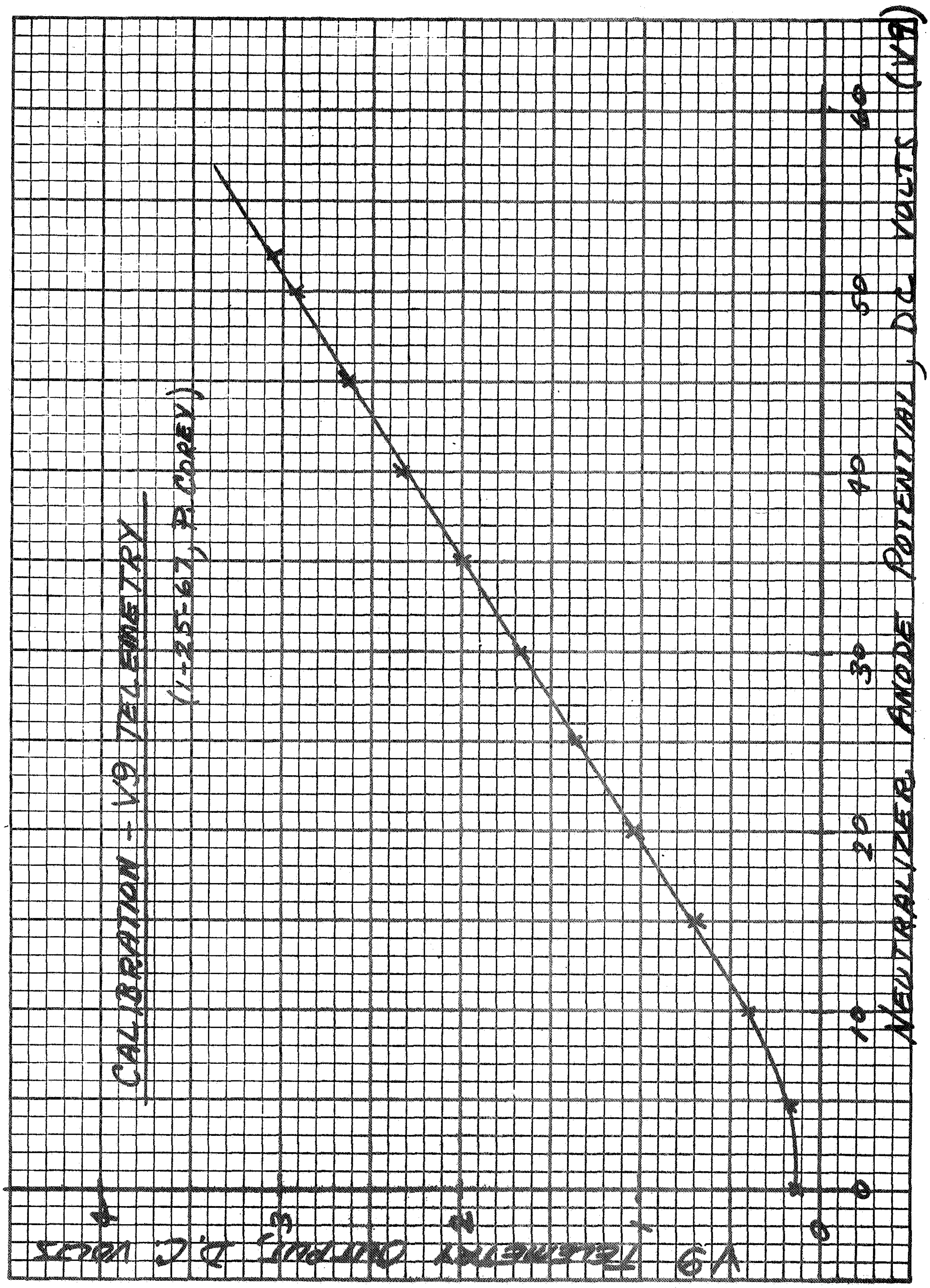

LIMITED TO 192 VOLTS BY ZENER (CR402)
VOLTAGE MULTIPLIER PREDOMINATES IN THIS REGION
"LINEAR" REGION
VOLT-AMP CHARACTERISTIC OF PROBE BIAS SUPPLY (V9), PLOTTED ON SEMI-LOG ABSCISSA TO SHOW DIFFERENT OPERATING REGIONS (45 V IN)
12-6-66 P. Corey
PROBE BIAS VOLTAGE (V9) IN VOLTS
200
180
160
140
120
100
80
60
40
20
0
.01
.1
1
10
100
PROBE BIAS CURRENT, DC MILLIAMPERES

FIG. 46



CALIBRATION - V9 TELEMETRY
(1-25-67, R. CORREY)
NEUTRALIZER ANODE POTENTIAL, DC VOLTS (IVA)
0
10
20
30
40
50
60
V9 TELEMETRY OUTPUT, D.C. VOLTS
0
1
2
3
4

FIG 47

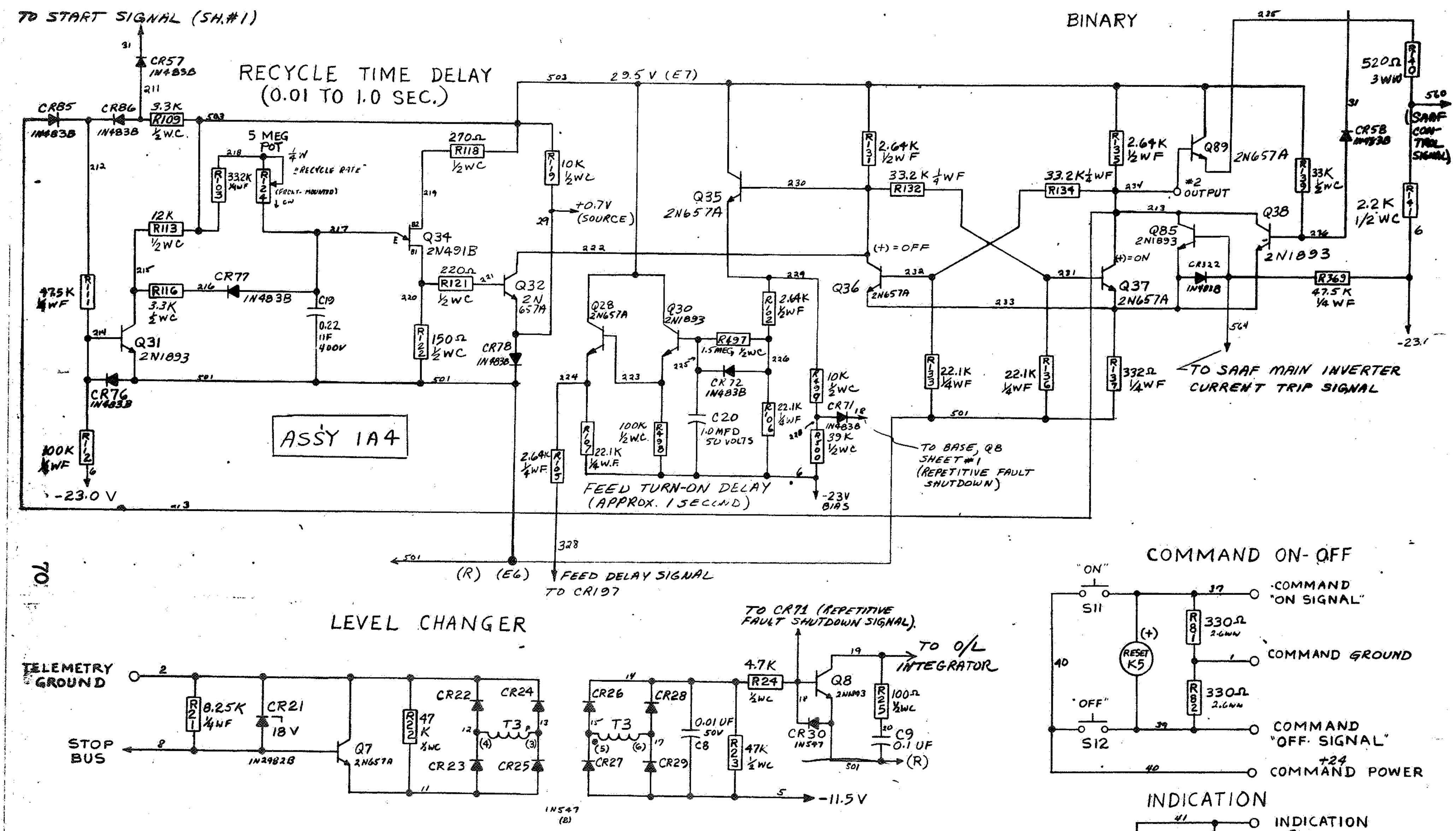

TO START SIGNAL (SH.#1)
RECYCLE TIME DELAY
(0.01 TO 1.0 SEC.)
BINARY
29.5 V (E7)
ASSY 1A4
FEED TURN-ON DELAY
(APPROX. 1 SECOND)
-23V BIAS
-23.0 V
-23.1
TO SAAF MAIN INVERTER CURRENT TRIP SIGNAL
TO BASE, Q8 SHEET #1 (REPETITIVE FAULT SHUTDOWN)
FEED DELAY SIGNAL TO CR197
+0.7V (SOURCE)
(SAAF CONTROL SIGNAL)
LEVEL CHANGER
TELEMETRY GROUND
STOP BUS
TO CR71 (REPETITIVE FAULT SHUTDOWN SIGNAL)
TO O/L INTEGRATOR
-11.5V
COMMAND ON-OFF
COMMAND "ON SIGNAL"
COMMAND GROUND
COMMAND "OFF SIGNAL"
+24 COMMAND POWER
INDICATION
INDICATION RETURN
+24V INDICATION POWER
NOTE - K5 CONTACT POSITION SHOWN IS THAT RESULTING FROM CLOSURE OF S12. K5 IS A LATCHING RELAY.

FIG 48

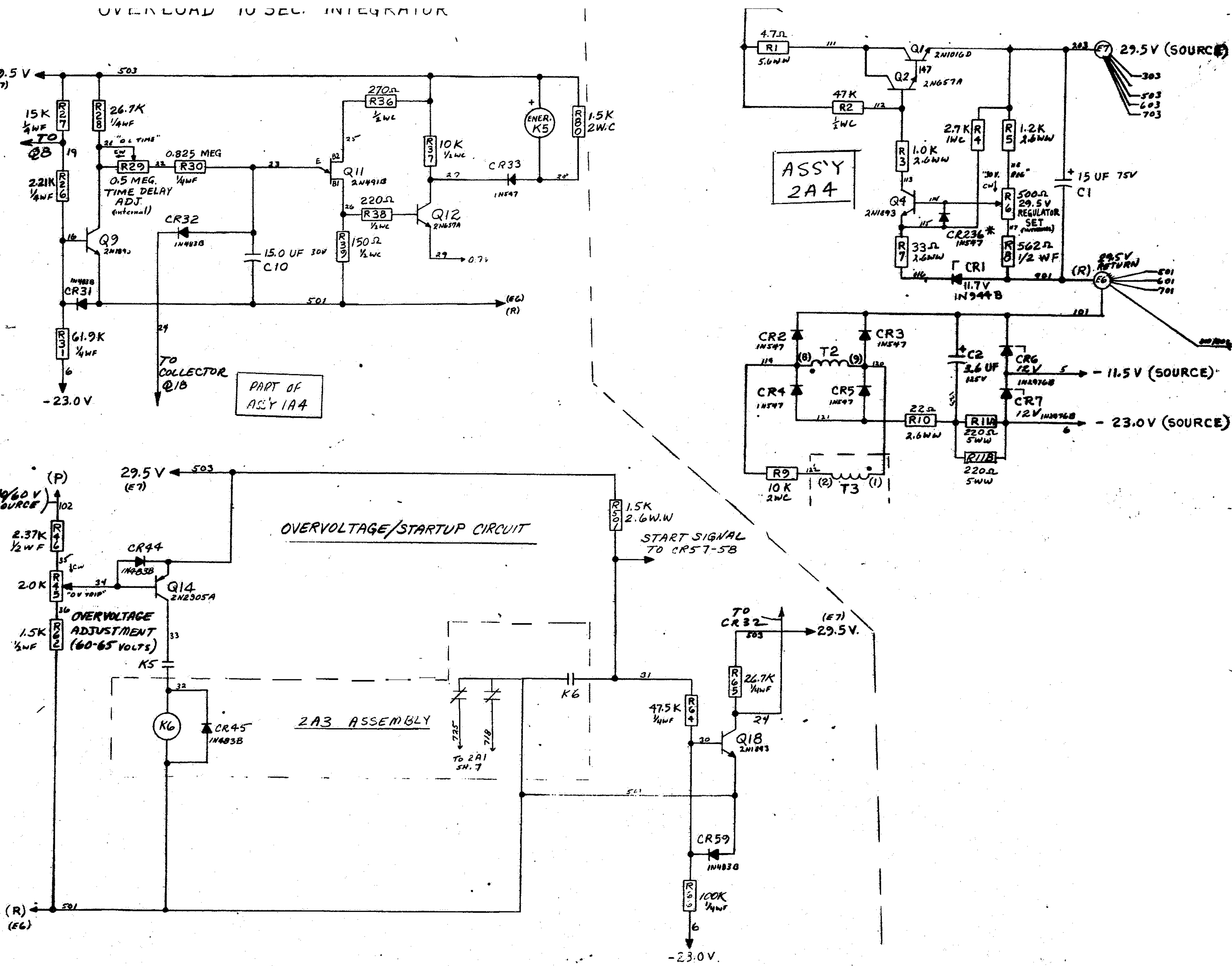

OVERLOAD 10 SEC. INTEGRATOR
PART OF ASS'Y 1A4
ASS'Y 2A4
OVERVOLTAGE/STARTUP CIRCUIT
2A3 ASSEMBLY
29.5 V (SOURCE)
- 11.5 V (SOURCE)
- 23.0 V (SOURCE)
29.5 V RETURN
TO COLLECTOR Q18
START SIGNAL TO CR57-58
TO CR32
TO Q8
TO 2A1 SH. 7
(40/60 V SOURCE)
OVERVOLTAGE ADJUSTMENT (60-65 VOLTS)
0.5 MEG. TIME DELAY ADJ. (internal)
500Ω 29.5 V REGULATOR SET
-23.0 V
29.5 V
(E7)
(E6)
(R)
(P)
K5
K6
ENER. K5
Q1 2N1016D
Q2 2N657A
Q4 2N1893
Q9 2N1893
Q11 2N491B
Q12 2N657A
Q14 2N2905A
Q18 2N1893
R1 4.7Ω 5.6WW
R2 47K 1WC
R3 1.0K 2.6WW
R4 2.7K 1WC
R5 1.2K 2.6WW
R6 500Ω
R7 33Ω 2.6WW
R8 562Ω 1/2 WF
R9 10 K 2WC
R10 22Ω 2.6WW
R11A 220Ω 5WW
R11B 220Ω 5WW
R26 2.21K 1/4WF
R27 15K 1/4WF
R28 26.7K 1/4WF
R29
R30 0.825 MEG 1/4WF
R31 61.9K 1/4WF
R36 270Ω 1/2WC
R37 10K 1/2WC
R38 220Ω 1/2WC
R39 150Ω 1/2WC
R46 2.37K 1/2WF
R45 2.0K
R62 1.5K 1/2WF
R50 1.5K 2.6W.W
R64 47.5K 1/4WF
R65 26.7K 1/4WF
R69 100K 1/4WF
R80 1.5K 2W.C
C1 15 UF 75V
C2 2.6 UF 125V
C10 15.0 UF 30V
CR1 11.7V 1N944B
CR2 1N547
CR3 1N547
CR4 1N547
CR5 1N547
CR6 12V 1N2976B
CR7 12V 1N2976B
CR236 1N547
CR31 1N483B
CR32 1N483B
CR33 1N547
CR44 1N483B
CR45 1N483B
CR59 1N483B
T2
T3

FIG. 49

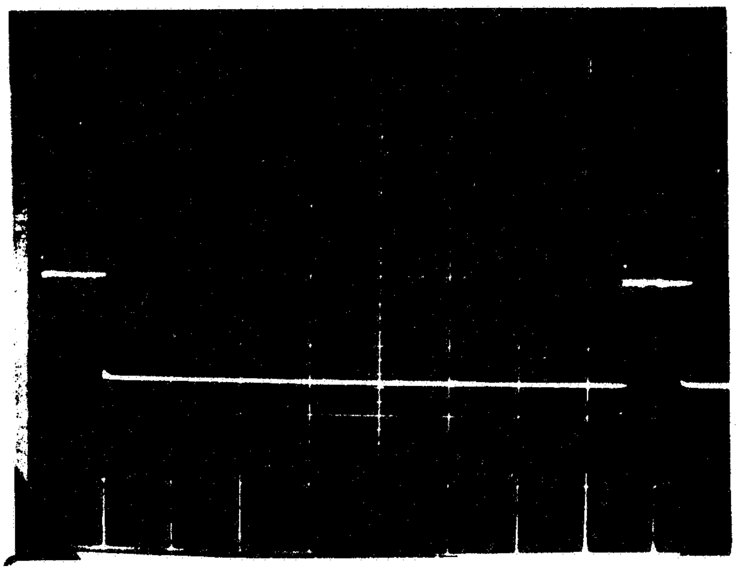


FIG. 50

FAULT RECYCLING. BASE VOLTAGE OF Q91, 1 VOLT/CM.

HORIZONTAL SCALE, 1 MILLISEC/CM.

"RECYCLE TIME" CONTROL SET FOR MINIMUM TIME, AND SAAF FAULT APPLIED.

F-75 (12-56)

GENERAL LOG SHEET

RUN No. 2
REQUEST No.

TITLE POWER CONDITIONER EFFICIENCY

OBSERVER P. COREY DATE SEPT. 20 1966 M

APPARATUS BREADBOARD

APPROVED BY

REMARKS CATHODE INVERTER WITH SEPARATE DRIVER/10 FT. TRANSM. LINE. ACCEL./SCREEN VOLTMETERS RECALIBRATED.

OBJECT TO MEET THE SPECIFIED $\eta = 0.80$ MIN.

		V	I		WATTS	
0						
1	SCREEN	3080	.186		573	
2	ACCEL	2010	.0374		75.2	
3	ANODE	25.8	6.9		178	
4	FEED	5.2	2.6		13.5	
5	CATHODE	4.0	37.8		151	
6	NEUT. K.	5.1	6.05		30.8	
7	NEUT VAP.	2.88	2.25		6.4	
8	NEUT. PROBE	OPEN			—	
9				TOTAL	1027.9	
10						$\eta = 0.808$
11	DC SOURCE	45.0	28.3		1272	
12						
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						
25						

FIG. 51

FOR USE OF G-E EMPLOYEES ONLY.

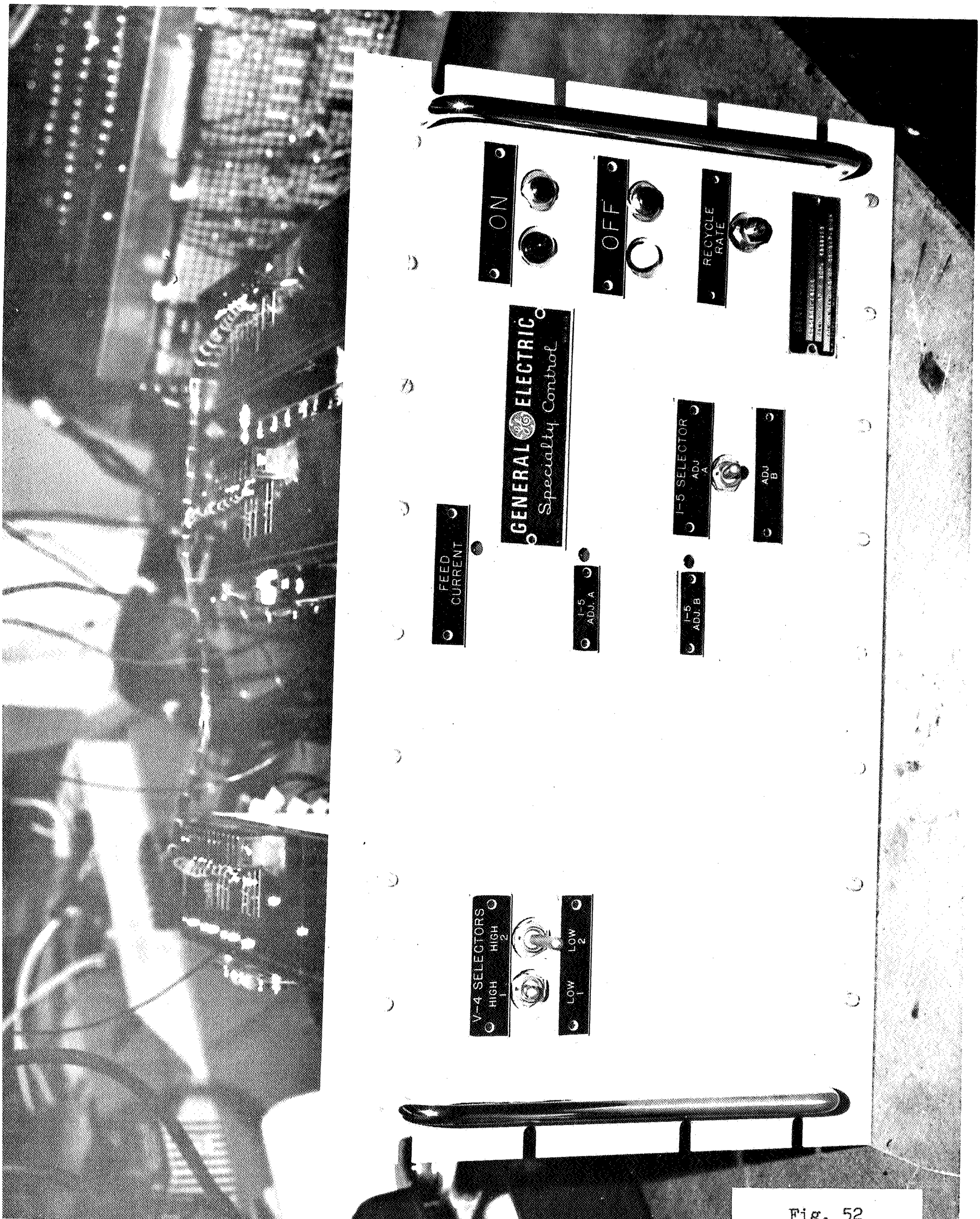

ON
OFF
RECYCLE RATE
GENERAL ELECTRIC
Specialty Control
FEED CURRENT
I-5 SELECTOR
ADJ A
ADJ B
I-5 ADJ. A
I-5 ADJ. B
V-4 SELECTORS
HIGH 1
HIGH 2
LOW 1
LOW 2

Fig. 52

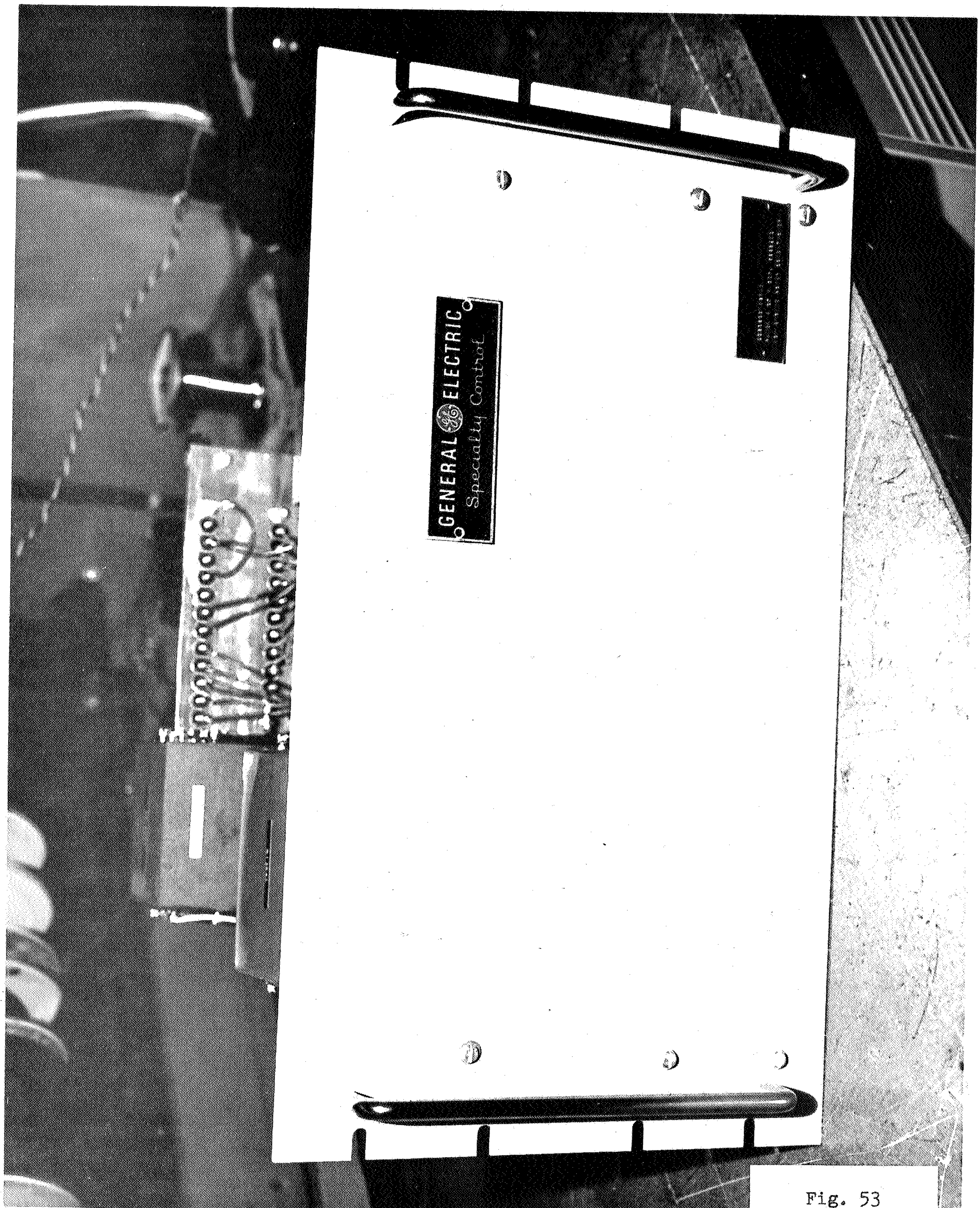


Fig. 53

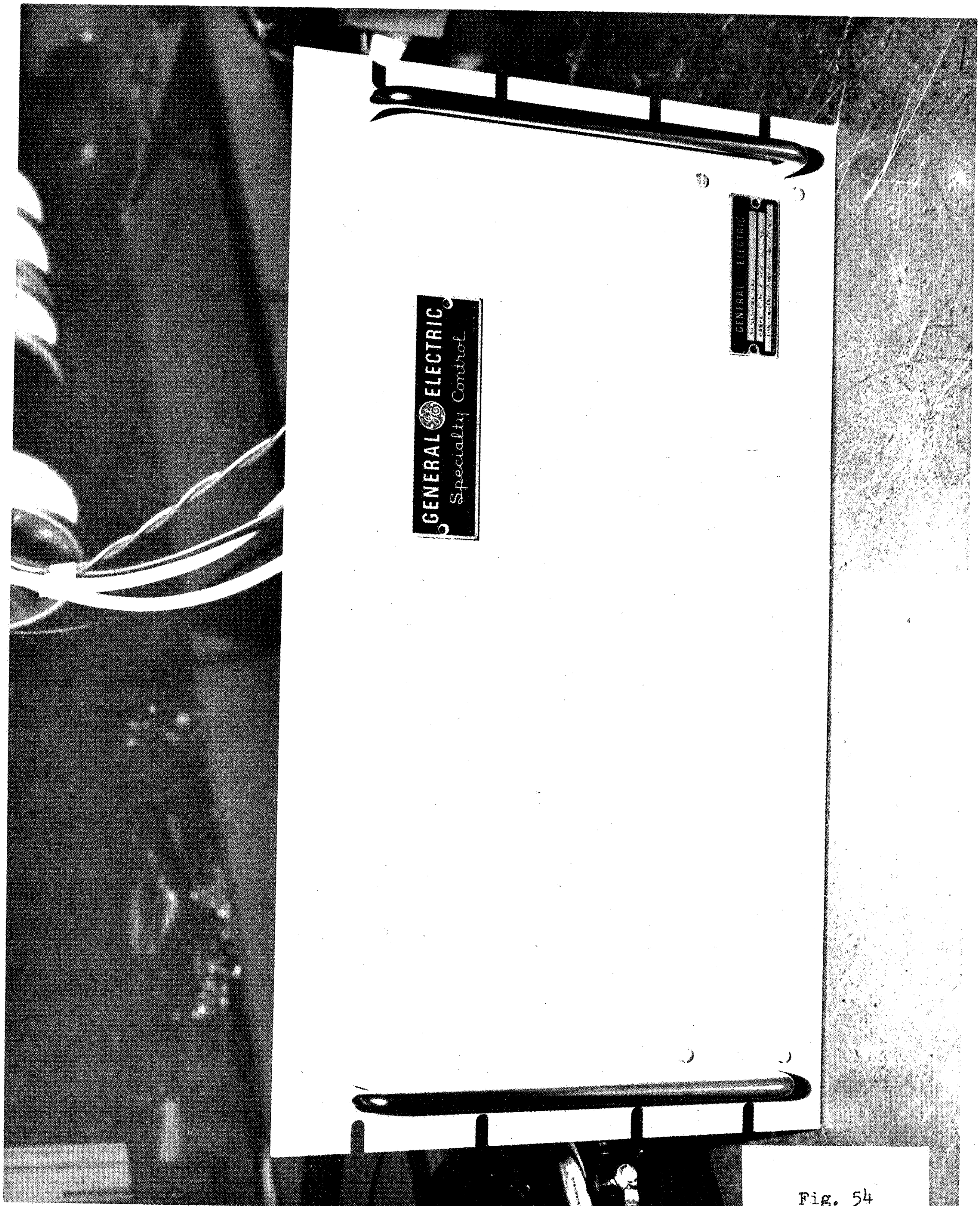


Fig. 54

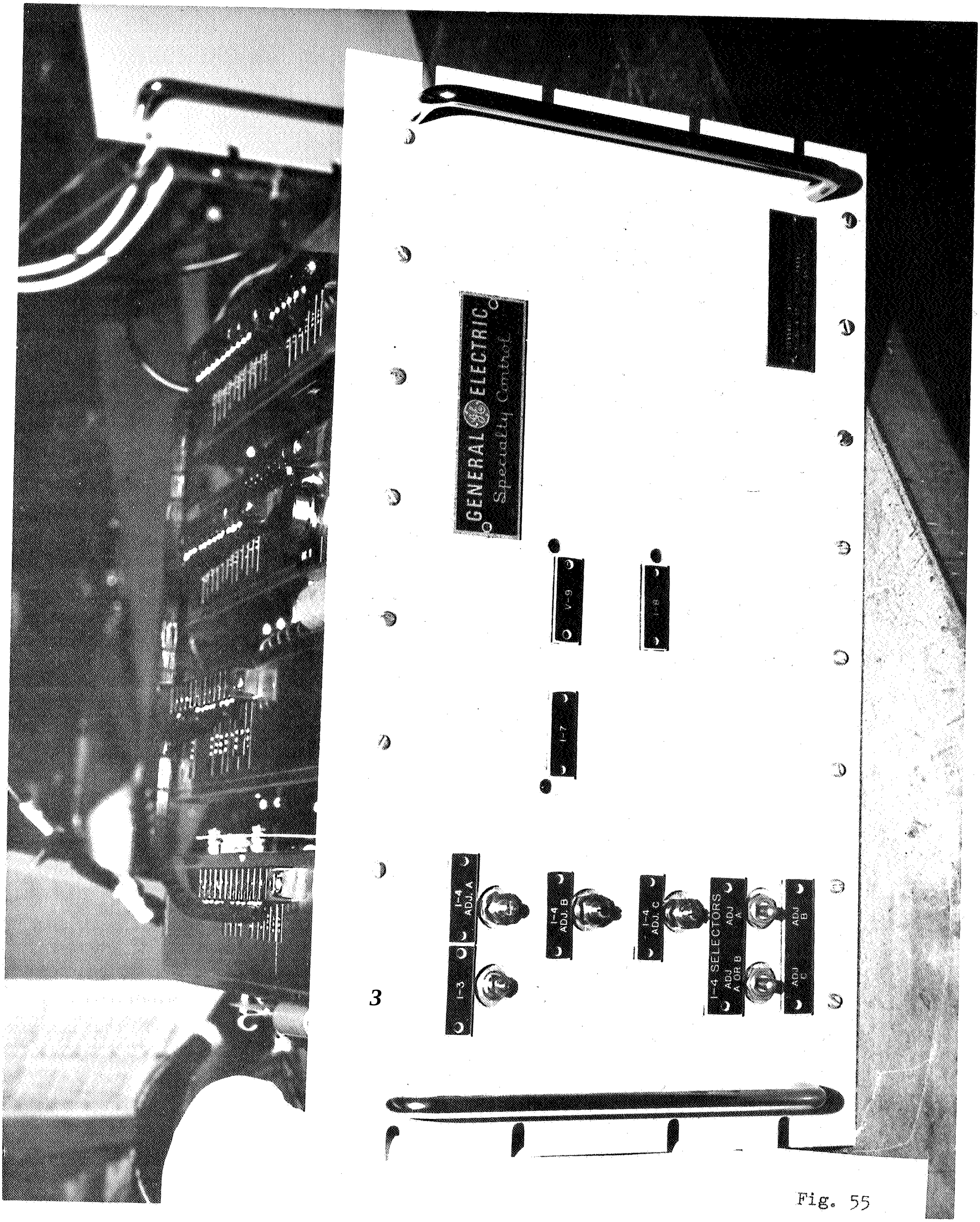

GENERAL ELECTRIC
Specialty Control
V-9
I-8
I-7
I-4 ADJ. A
I-3
I-4 ADJ. B
I-4 ADJ. C
I-4 SELECTORS
ADJ A OR B
ADJ A
ADJ B
ADJ C
3

Fig. 55

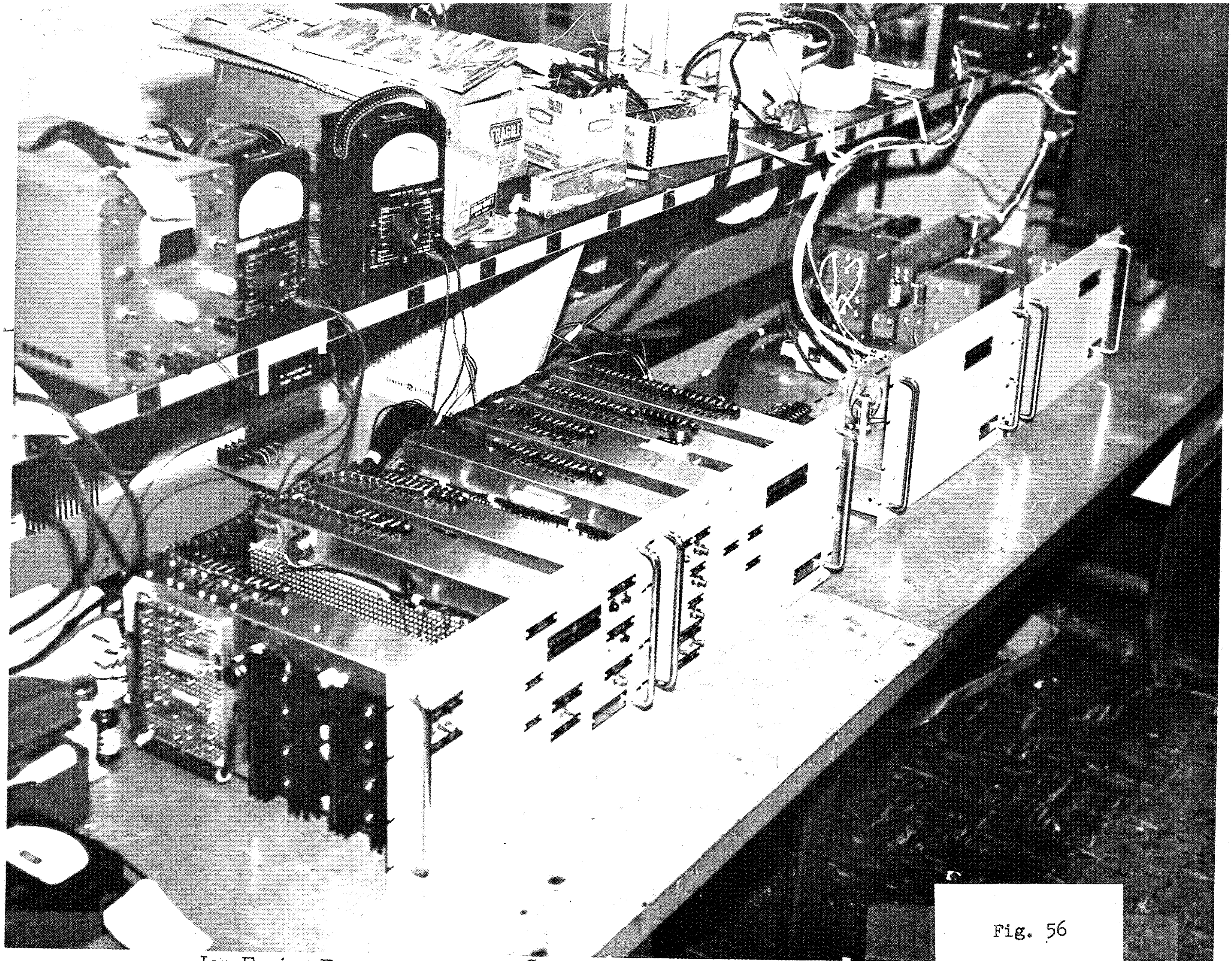


Fig. 56

Ion Engine Power Conditioner System Operating Into Test Console Loads

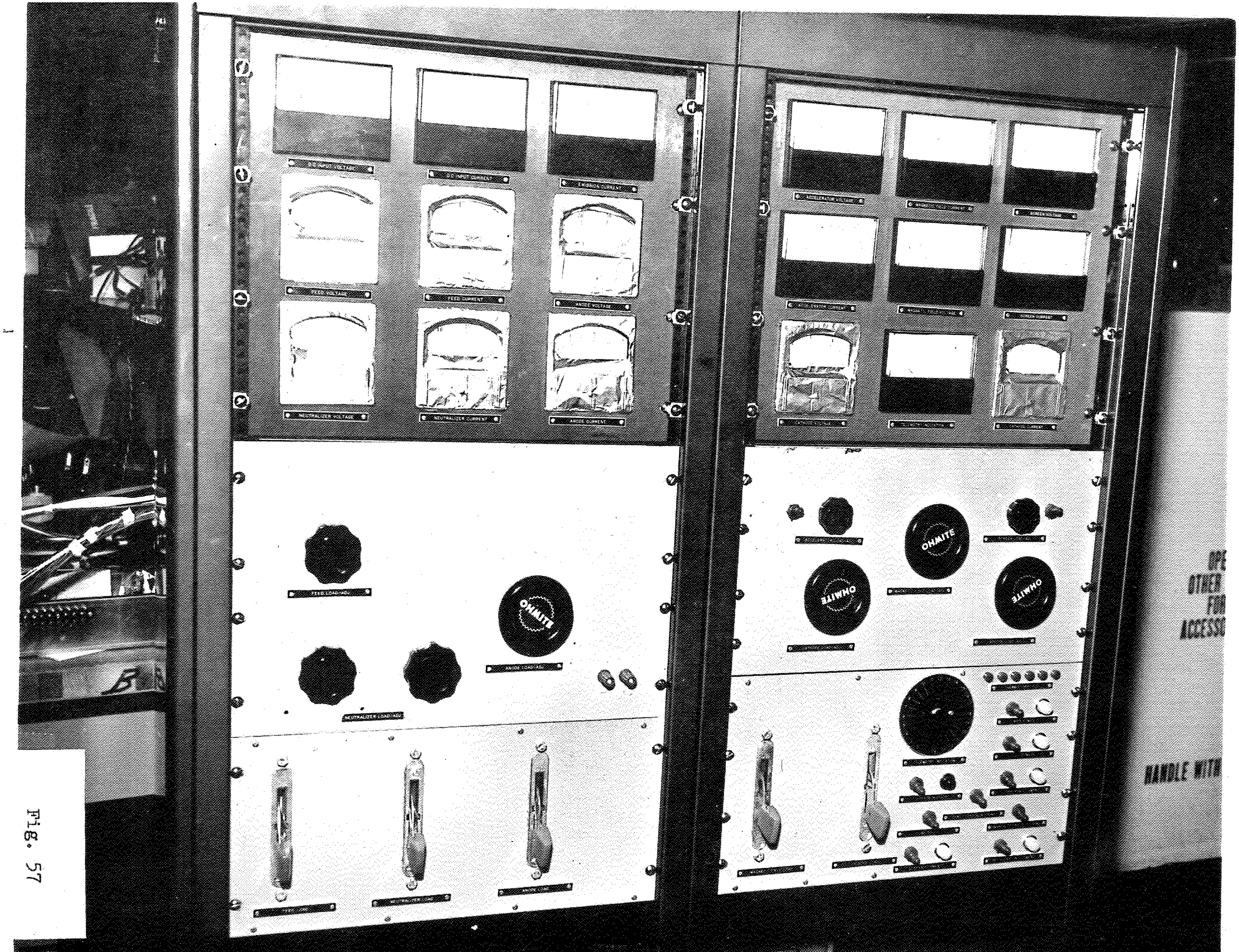
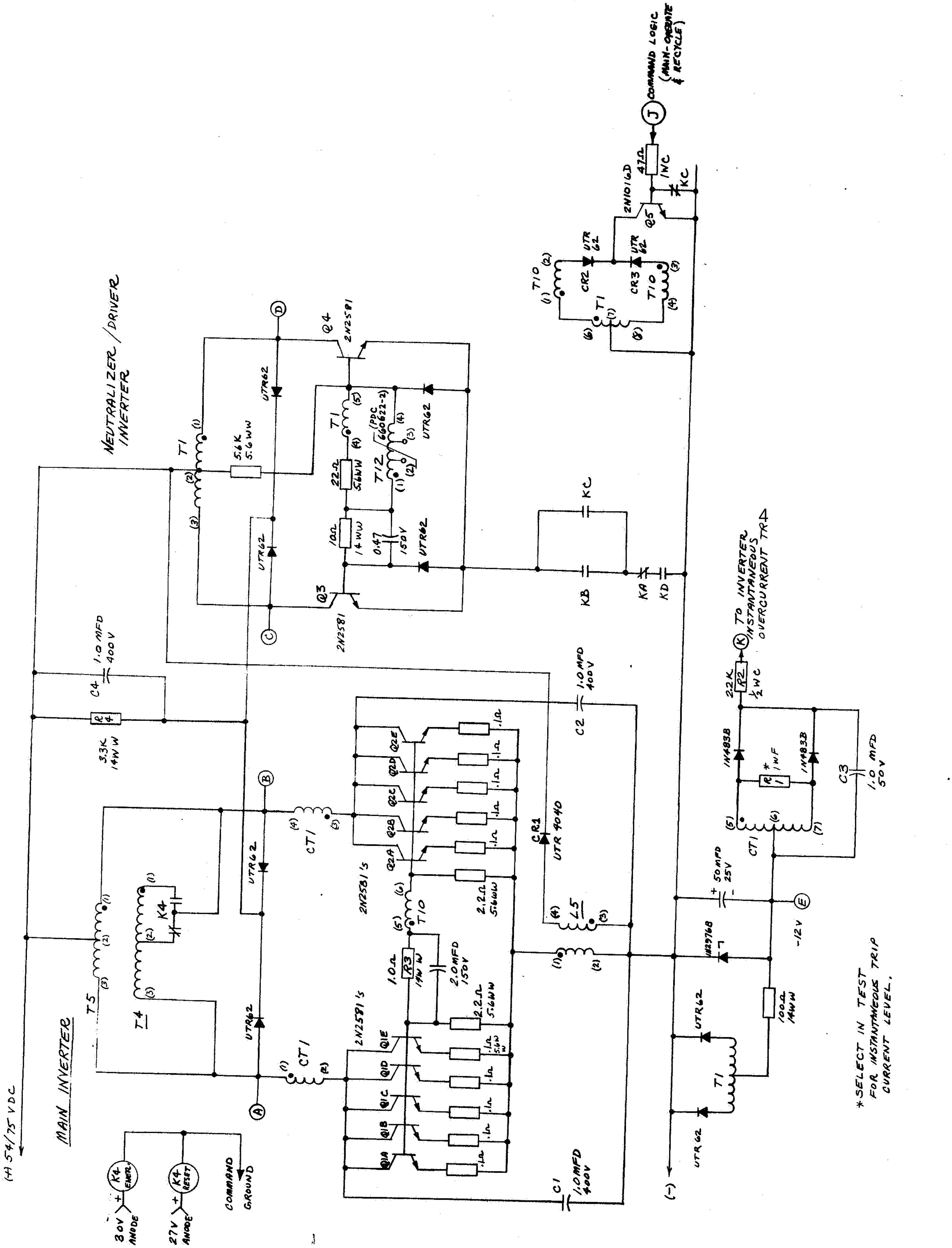


Fig. 57

Fig. VIII-1 Control Console, Front View, Showing Instruments and Controls

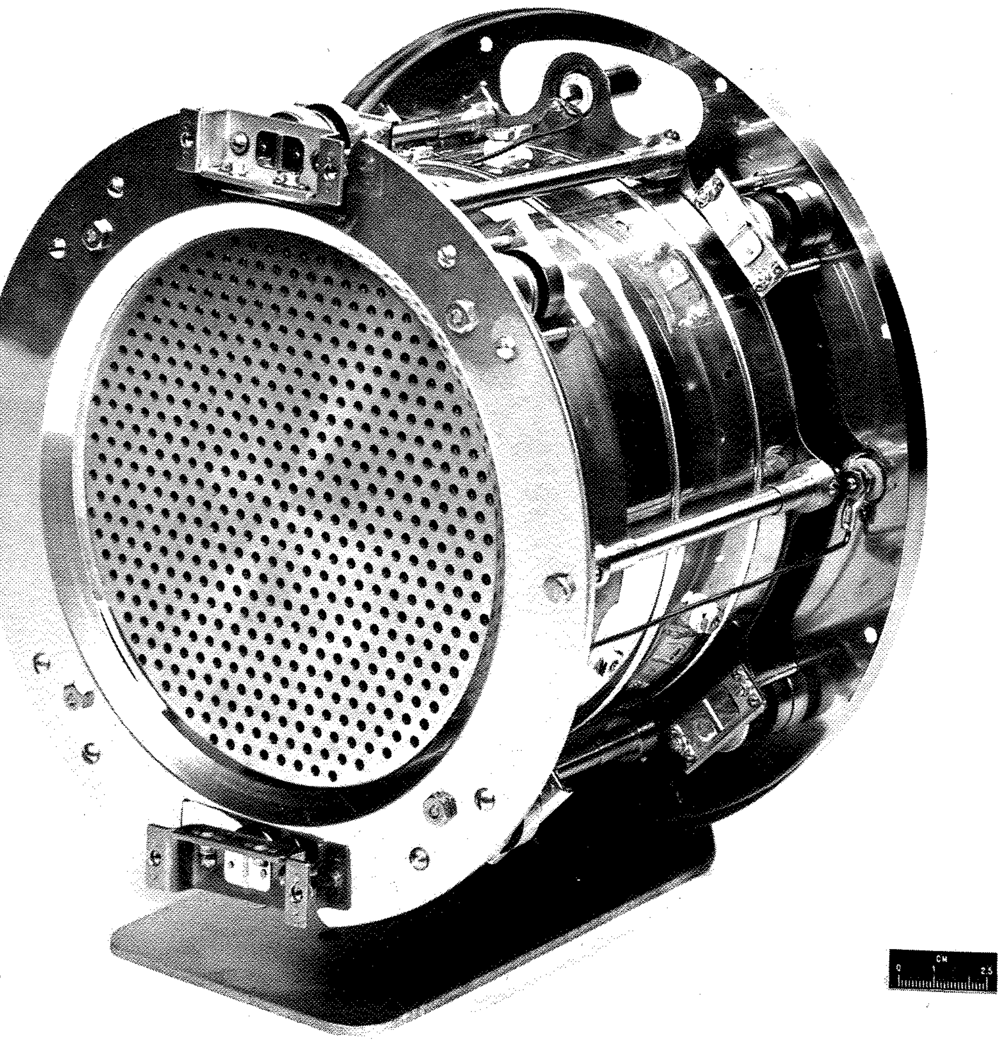
Fig. 58

Fig. VIII-2 Control Console, Rear View, Door Open, Showing Loads



MAIN INVERTER
NEUTRALIZER / DRIVER INVERTER
(+) 54/75 VDC
(-)
COMMAND LOGIC (MAIN-OPERATE & RECYCLE)
TO INVERTER INSTANTANEOUS OVERCURRENT TR4
COMMAND GROUND
30V ANODE
27V ANODE
K4 ENER.
K4 RESET
2N2581's
2N2581
2N1016D
UTR62
UTR 4040
1N483B
1N2976B
1.0 MFD 400V
2.0 MFD 150V
50 MFD 25V
1.0 MFD 50V
3.3K 14WW
5.6K 5.6WW
22K ½WC
47Ω 1WC
100Ω 14WW
-12V
*SELECT IN TEST FOR INSTANTANEOUS TRIP CURRENT LEVEL.

Fig. 59



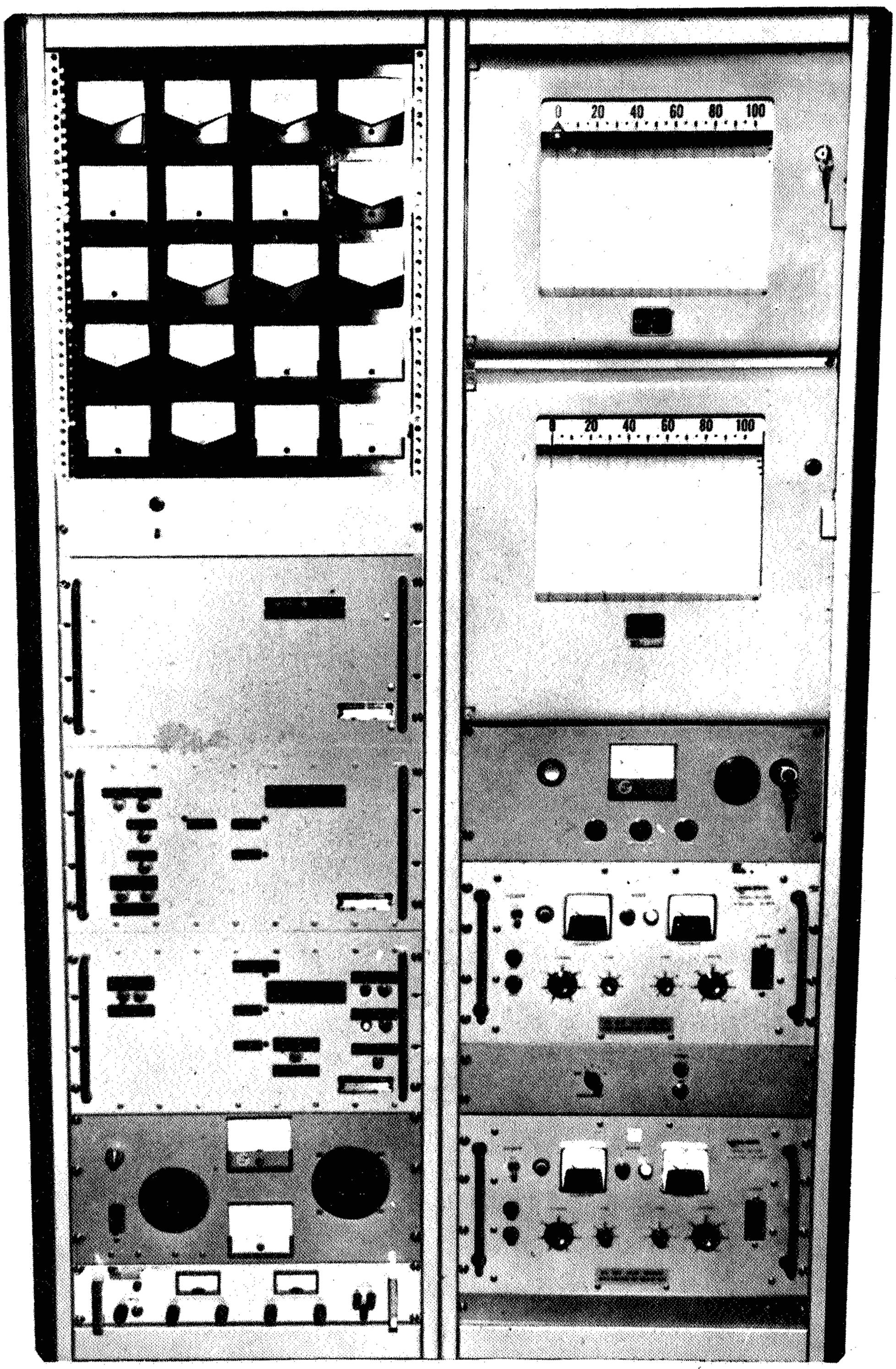
Sert II Ion Thrustor

Powered by NASA Lim

Test Console. Neutralizer

and Feed System not Shom

Fig. 60



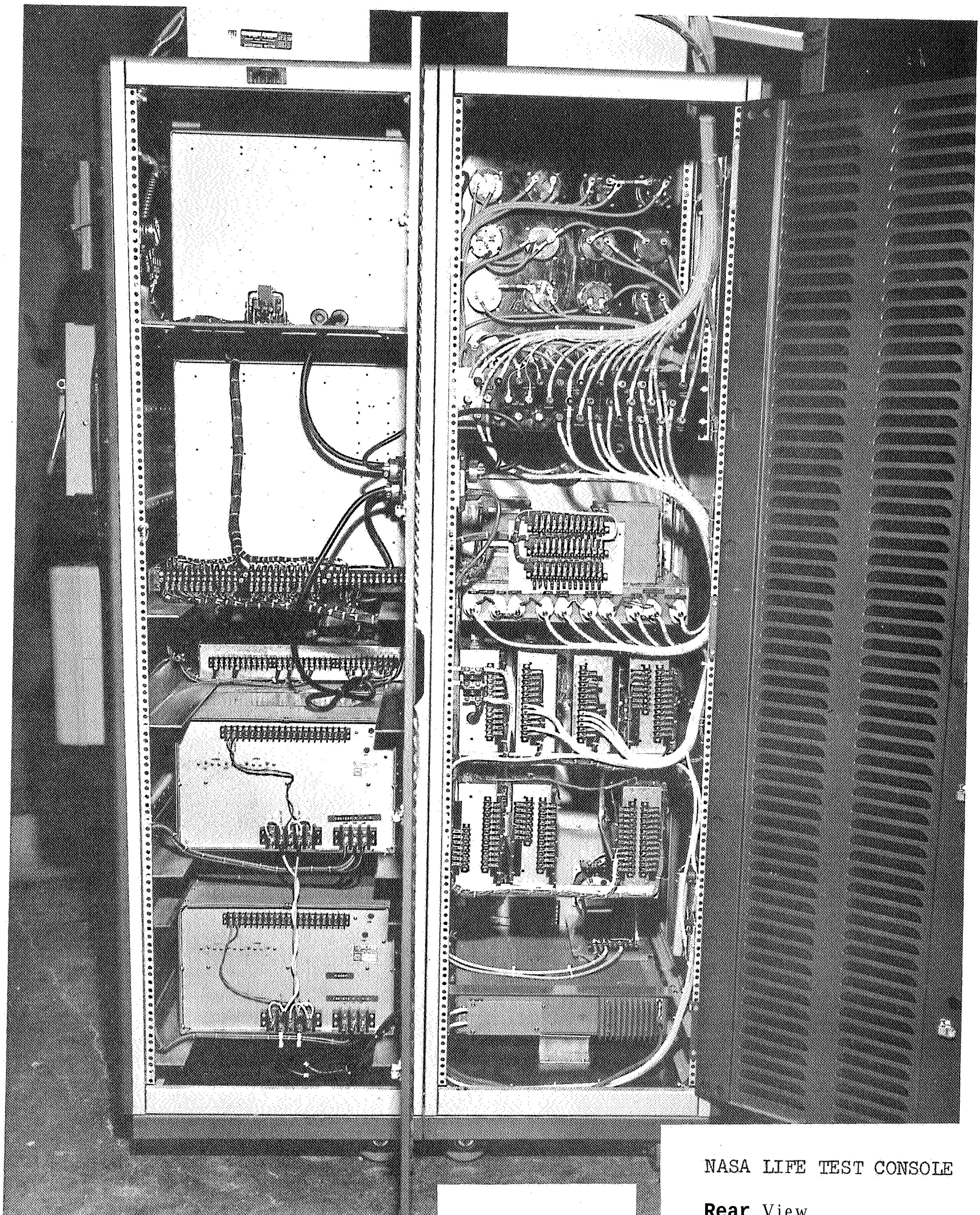
NASA LIFE TEST CONSOLE

Used to Operate Sert II Ion Thrustor

During 549 Hour Duration Test

Fig. 61

NASA
C-67-280



NASA LIFE TEST CONSOLE

Rear View

Fig, 62

APPENDIX A

REFERENCES

1. Ernsberger, G, W.: An Experimental Model. of a 2 KW, 2500 Volt Power Converter for Ion Thrustors Using Silicon Transistors in a Pulse-Width-Modulated Bridge Inverter. NASA CR-54217 , 1965.

2, Elder, F, A,; and Staley, L. E.: An Experimental Model of a 2 KW, 2500 Volt Power Converter Tor Ion Thrustors Using Gate Controlled Switches in Two Phase-Shifted Parallel Inverters. NASA CR-54216, 1965.

3. Lalli, Vincent R,: Ion Engine Subsystem Reliability Procedure. NASA TM X-52055, 1965.

4. Payson, W. H.: Power Conditioning and Control System, Interim Design and Development Report. NASA CR-64161, 1965.

5. Davis, J.; and Forrester, Dr. A. T.: Ion Thrustor Program, Technical Report AFAPL-TR-65-87 , Project 661-A. NASA AD-472336, 1965.

6. Mickelsen, William R. : Advanced Electric Propulsion Research, Interim Report. NASA CR-77939 , 1966.

7. Brown, H.; and Taylor, J. R.: Navigator Study of Electric Propulsion for Unmanned Scientific Missions. NASA CR-565 , 1966.

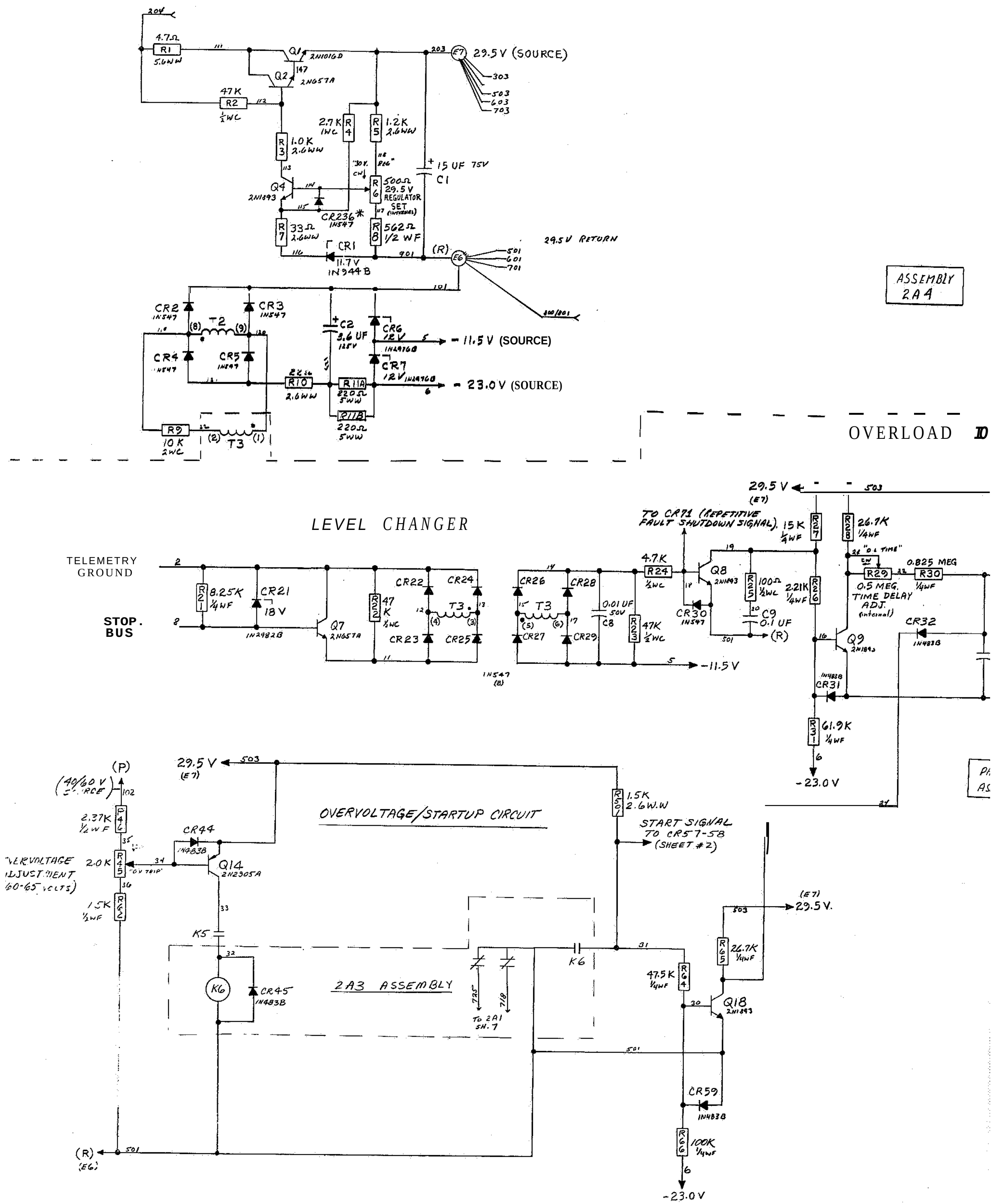
8. Reader, P. D.: Investigation of a 10-Centimeter-Diameter Electron-Bombardment Ion Rocket. NASA TN D-1163 , 1962.

9. Mickelsen, W. R.; and Kaufman, H. R.: Status of Electrostatic Thrustors for Space Propulsion NASA TN D-2172, 1964.

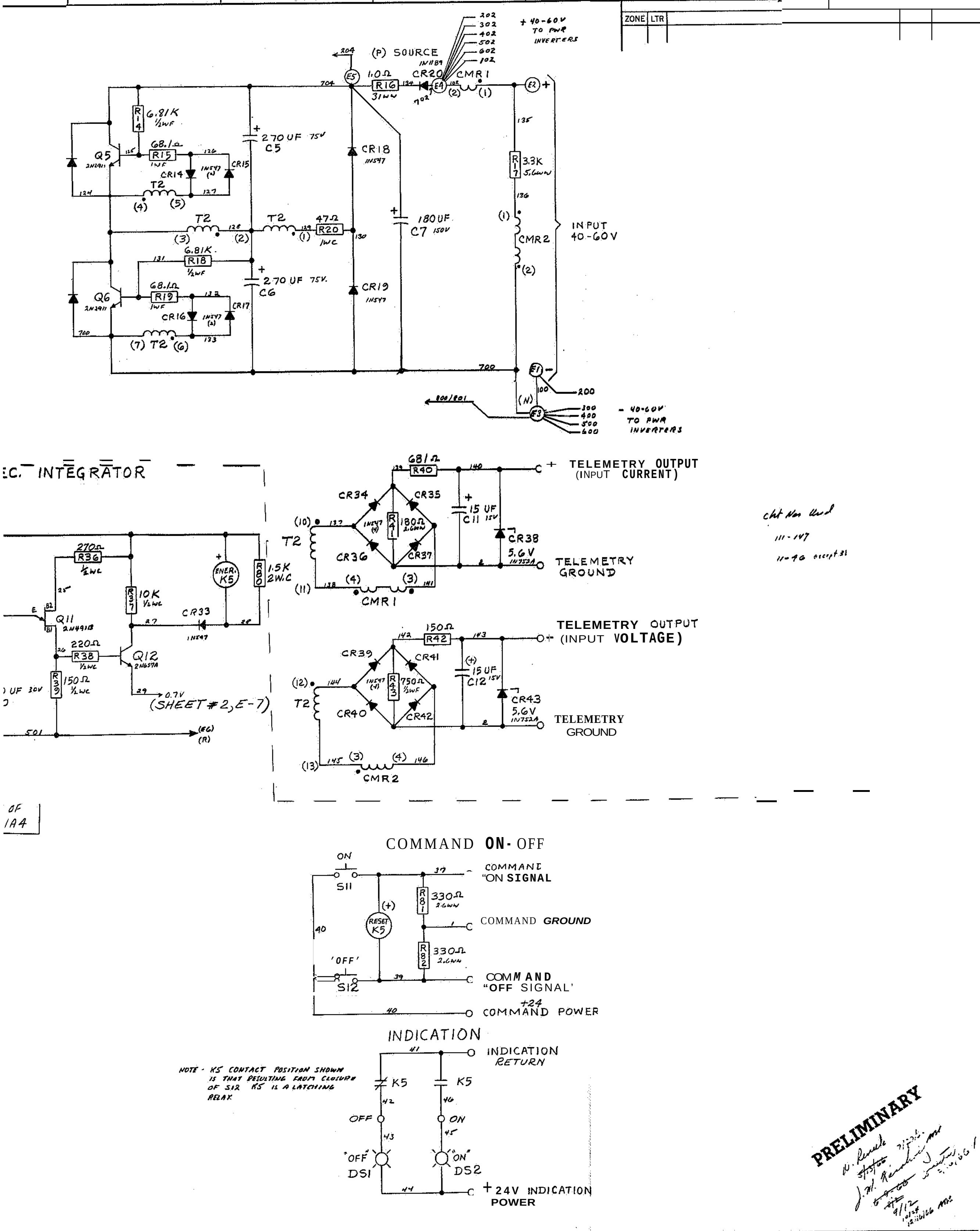
10. Kaufman, H. R.: Performance Correlation for Electron-Bombardment Ion Sources. NASA TN D-3041, 1965.

APPENDIX B

This appendix contains the complete schematic diagrams for the entire power conditioner as delivered.



29.5 V (SOURCE)
29.5 V RETURN
ASSEMBLY 2A4
- 11.5 V (SOURCE)
- 23.0 V (SOURCE)
OVERLOAD
LEVEL CHANGER
TELEMETRY GROUND
STOP BUS
TO CR71 (REPETITIVE FAULT SHUTDOWN SIGNAL)
TIME DELAY ADJ.
0.5 MEG.
0.825 MEG
-11.5 V
-23.0 V
OVERVOLTAGE/STARTUP CIRCUIT
START SIGNAL TO CR57-58 (SHEET #2)
2A3 ASSEMBLY
To 2A1 SH. 7
29.5 V
(E7)
(P)
(R)
(E6)



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES—
TOLERANCES ON:
2-PLACE DECIMALS ±
3-PLACE DECIMALS ±
ANGLES ±
FRACTIONS ±
ALL SURF ✓
MATERIAL—

INDEX IS ON SHEET 8

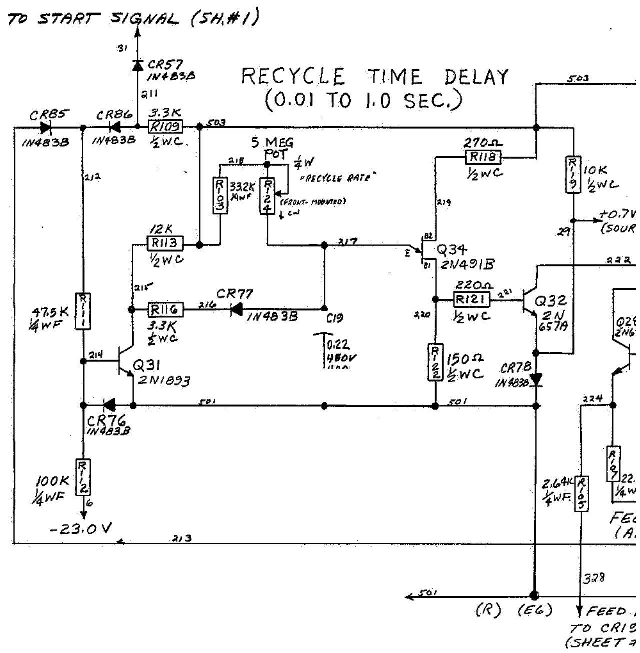
SIGNATURES	DAY	MO	YR
DRAWN W. Bryant	5	4	66
CHECKED			
ISSUED			
ENGRG D. Casey	19	12	66
MFG			
MATLS			

3S2020BM121A1

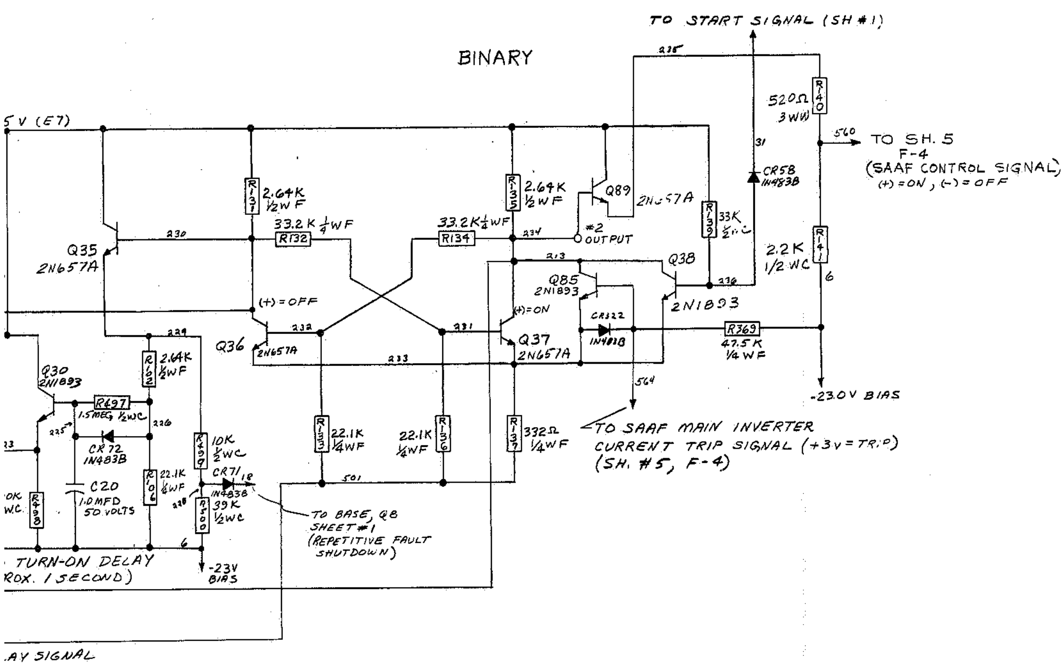
GENERAL ELECTRIC
SPECIALTY CONTROL DEPT LOC WAYNESBORO, VA.

ELEMENTARY DIAGRAM
ICN ENGINE POWER CONDITIONER
(SERIES REGULATOR - BIAS - LEVEL CHANGE. OV/STARTUP - 10 SEC O.L. - COMMANDS)

SIZE F | CODE IDENT NO. 01526 | 44F242512
SCALE | SHEET 1 OF 8

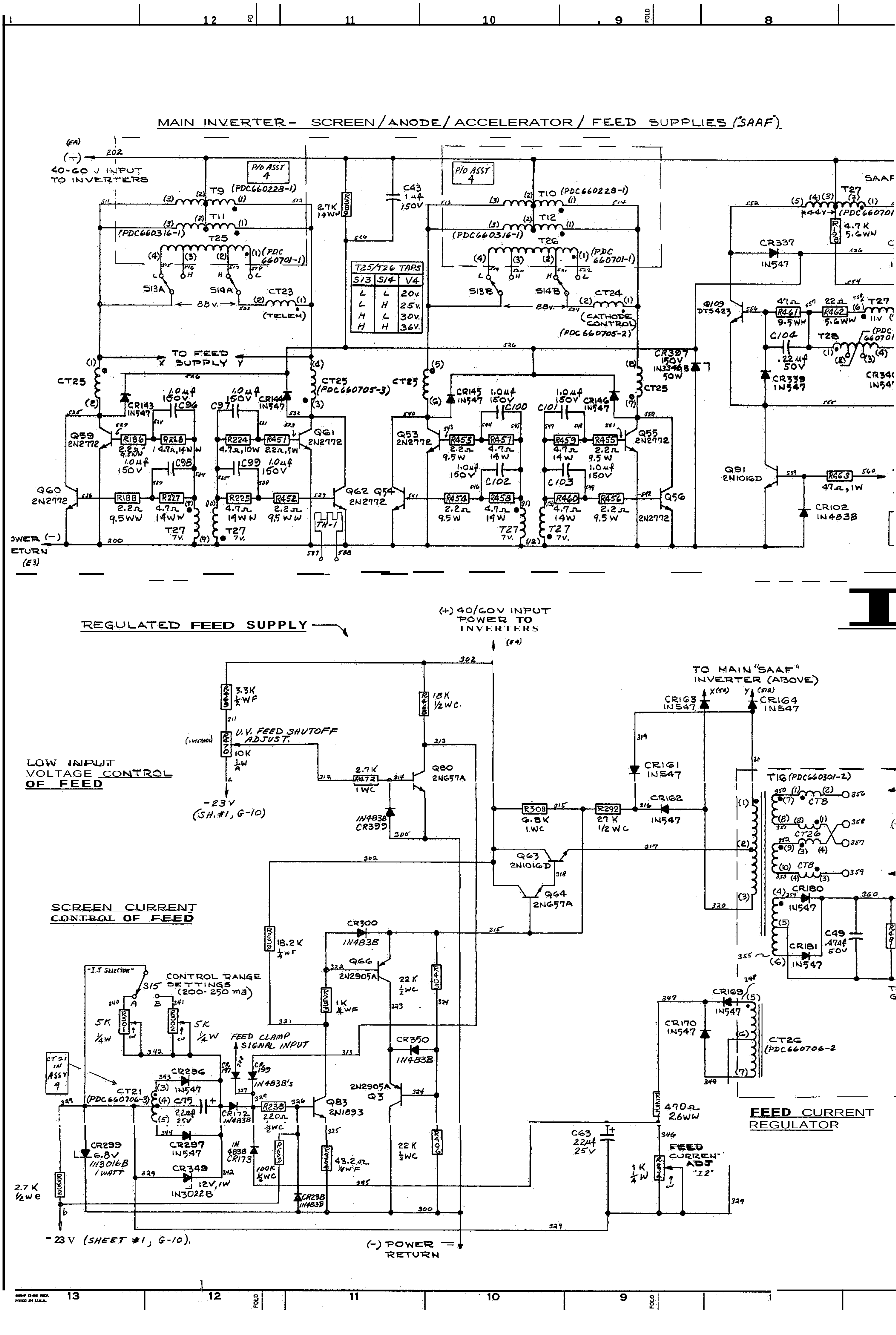


TO START SIGNAL (SH.#1)
CR57
1N483B
RECYCLE TIME DELAY
(0.01 TO 1.0 SEC.)
CR85
1N483B
CR86
1N483B
3.3K
R109
½W.C.
5 MEG
POT
¼W
"RECYCLE RATE"
R103
33.2K
¼WF
R124
270Ω
R118
½WC
R119
10K
½WC
+0.7V
12K
R113
½WC
Q34
2N491B
220Ω
R121
½WC
Q32
2N
657A
R111
47.5K
¼WF
R116
3.3K
½WC
CR77
1N483B
C19
0.22
480V
Q31
2N1893
R122
150Ω
½WC
CR78
CR76
1N483B
R112
100K
¼WF
-23.0V
2.64K
¼WF.
R105
R107
(R) (E6)
FEED
TO CR1
(SHEET



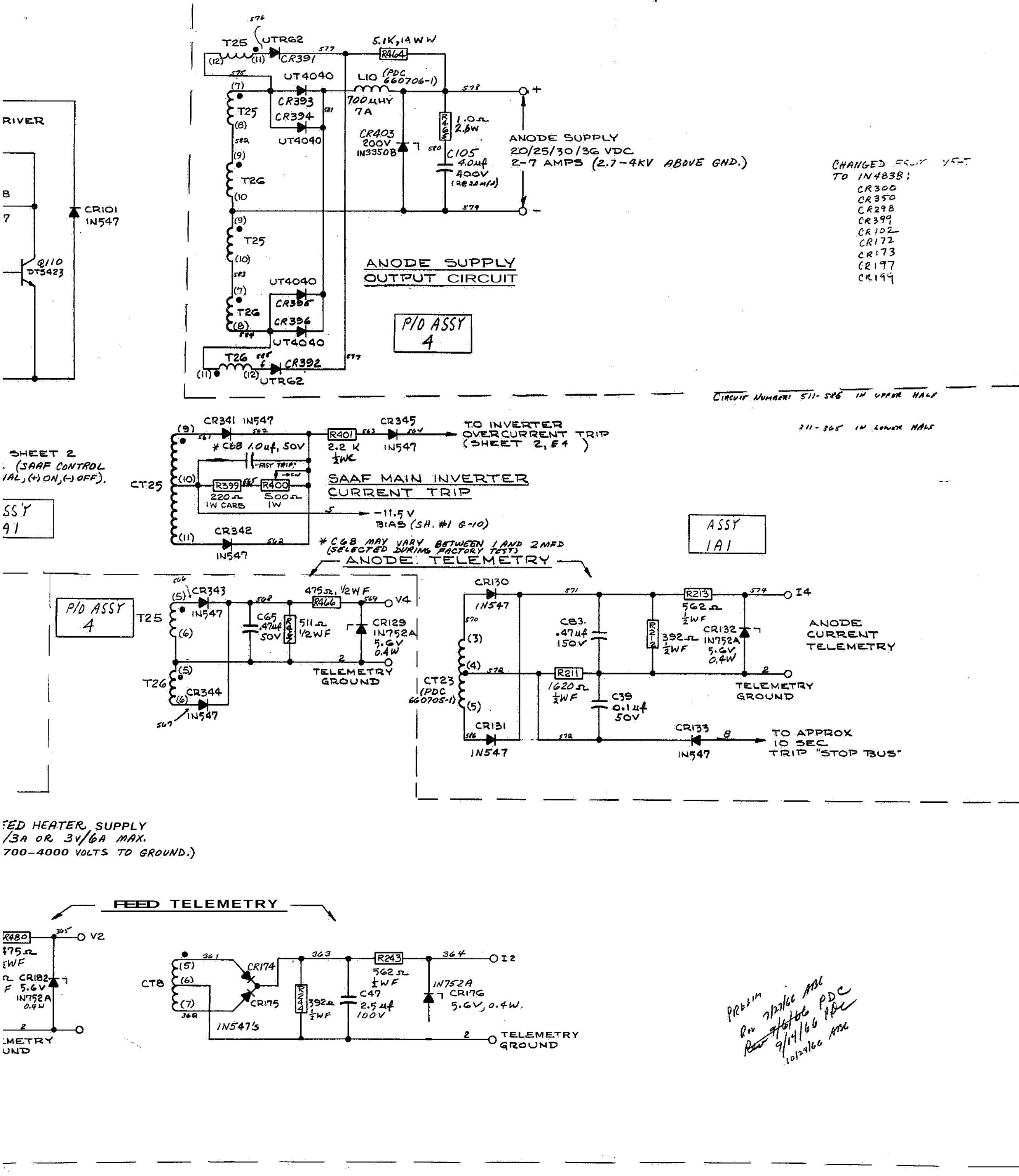
PRELIMINARY

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES— TOLERANCES ON: 2-PLACE DECIMALS ± 3-PLACE DECIMALS ± ANGLES ± FRACTIONS ± ALL SURF ✓ MATERIAL—	SIGNATURES DAY MO YR DRAWN W. Bryant 6 4 66 CHECKED ISSUED ENGRG P.D. Conry 19 12 66 MFG MATLS 3S2020BM121A1	GENERAL ELECTRIC SPECIALTY CONTROL DEPT LOC WAYNESBORO, VA. ELEMENTARY DIAGRAM ION ENGINE POWER CONDITIONER (RECYCLE TIMER - BINARY) SIZE F CODE IDENT NO. 01526 44F242512 SCALE SHEET 2 OF 8



S13	S14	V4
L	L	20v.
L	H	25v.
H	L	30v.
H	H	36v.

ZONE	LTR	DESCRIPTION	DATE	APPROVED



UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES—
TOLERANCES ON:
2-PLACE DECIMALS ±
3-PLACE DECIMALS ±
ANGLES ±
FRACTIONS ±
ALL SURF ✓
MATERIAL—

SIGNATURES	DAY	MO	YR
DRAWN [signature]	5	7	66
CHECKED			
ISSUED			
ENGR P. D. Corey	17	12	66
MFG			
MATLS			

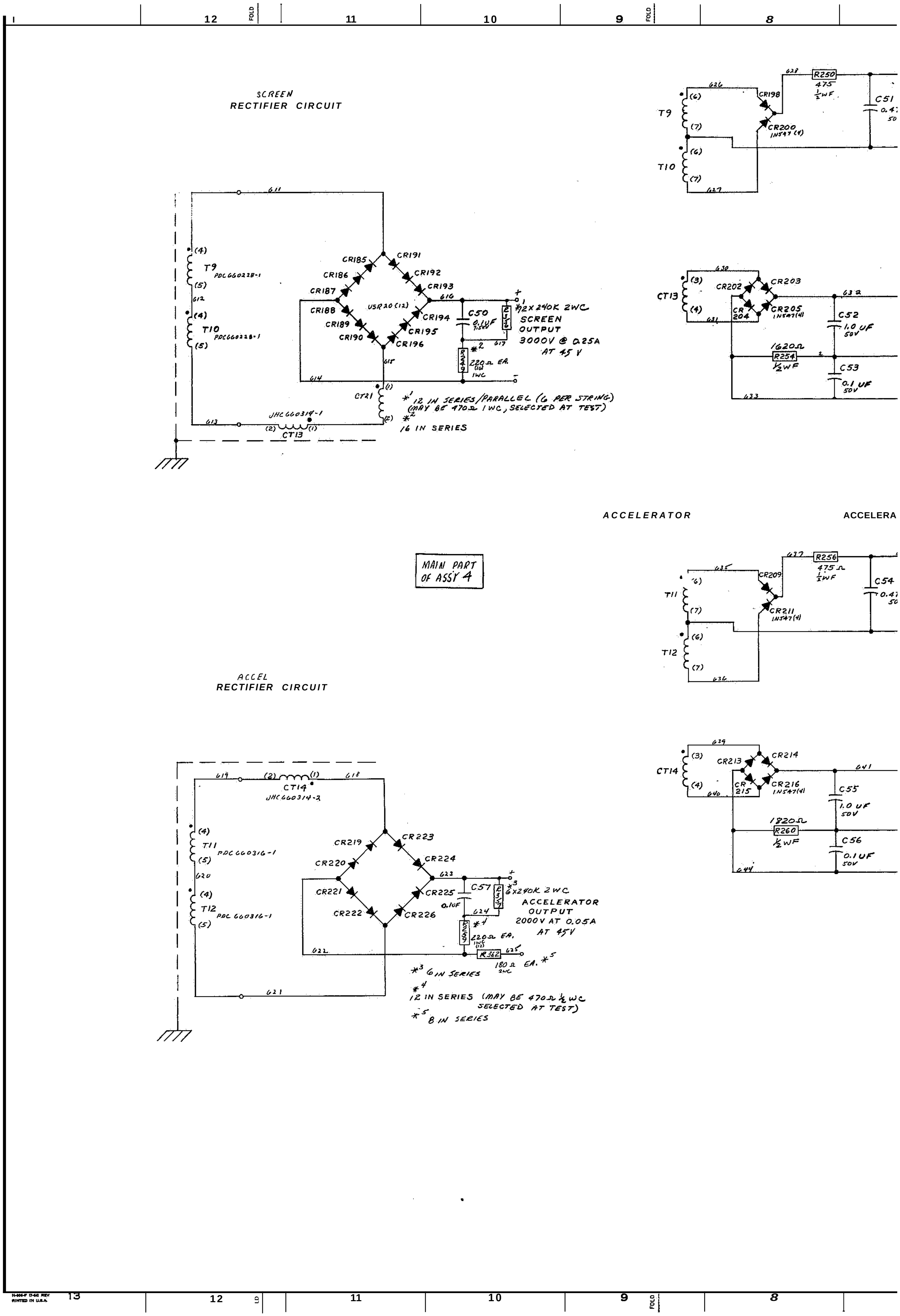
352020BM121A1

GENERAL ELECTRIC
SPECIALTY CONTROL DEPT LOC WAYNESBORO, VA.

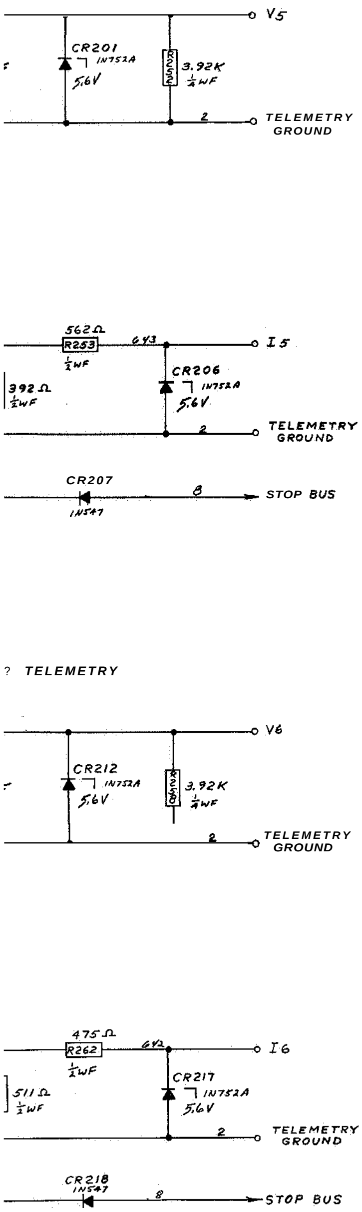
ELEMENTARY DIAGRAM
ION ENGINE POWER CONDITIONER
(SCREEN/ANODE/ACCEL./FEED SUPPLY)

SIZE F | CODE IDENT NO. 01526 | 44F242512

SCALE | SHEET 5 OF 8



SCREEN
RECTIFIER CIRCUIT
T9
PDC660228-1
T10
PDC660228-1
CR185
CR186
CR187
CR188
CR189
CR190
CR191
CR192
CR193
CR194
CR195
CR196
USR20 (12)
C50
0.1UF
*1 12x240K 2WC
SCREEN
OUTPUT
3000V @ 0.25A
AT 45 V
*2 220Ω EA.
1WC
CT21
JHC660314-1
CT13
*1 12 IN SERIES/PARALLEL (6 PER STRING)
(MAY BE 470Ω 1WC, SELECTED AT TEST)
*2 16 IN SERIES
MAIN PART
OF ASSY 4
ACCEL
RECTIFIER CIRCUIT
CT14
JHC660314-2
T11
PDC660316-1
T12
PDC660316-1
CR219
CR220
CR221
CR222
CR223
CR224
CR225
CR226
C57
0.1UF
*3 6x240K 2WC
ACCELERATOR
OUTPUT
2000V AT 0.05A
AT 45V
*4 220Ω EA.
R362
180Ω EA. *5
*3 6 IN SERIES
*4 12 IN SERIES (MAY BE 470Ω ½WC
SELECTED AT TEST)
*5 8 IN SERIES
T9
T10
CR198
CR200
1N547 (4)
R250
475
½WF
C51
CT13
CR202
CR203
CR204
CR205
1N547(4)
C52
1.0 UF
50V
1620Ω
R254
½WF
C53
0.1 UF
50V
ACCELERATOR
ACCELERA
T11
T12
CR209
CR211
1N547(4)
R256
475Ω
½WF
C54
CT14
CR213
CR214
CR215
CR216
1N547(4)
C55
1.0 UF
50V
1820Ω
R260
½WF
C56
0.1UF
50V
12
11
10
9
8
FOLD



chk no 611-644 used
not used 634

Preliminary
W. Resnik

7-27-66
7-20-66 RRK
9/14/66 PDC
10/24/66
Corrected 12/10/66
PDC

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES— TOLERANCES ON: 2-PLACE DECIMALS ± 3-PLACE DECIMALS ± ANGLES ± FRACTIONS ±	ALL SURF ✓	SIGNATURES	DAY	MO	YR
		DRAWN Eleanor Ellison	12	4	66
		CHECKED			
		ISSUED			
		ENGR P. D. Corey	19	12	66
MATERIAL—		MFG			
		MATLS			

3S2020BM121A1

GENERAL ELECTRIC
SPECIALTY CONTROL DEPT LOC WAYNESBORO, VA.

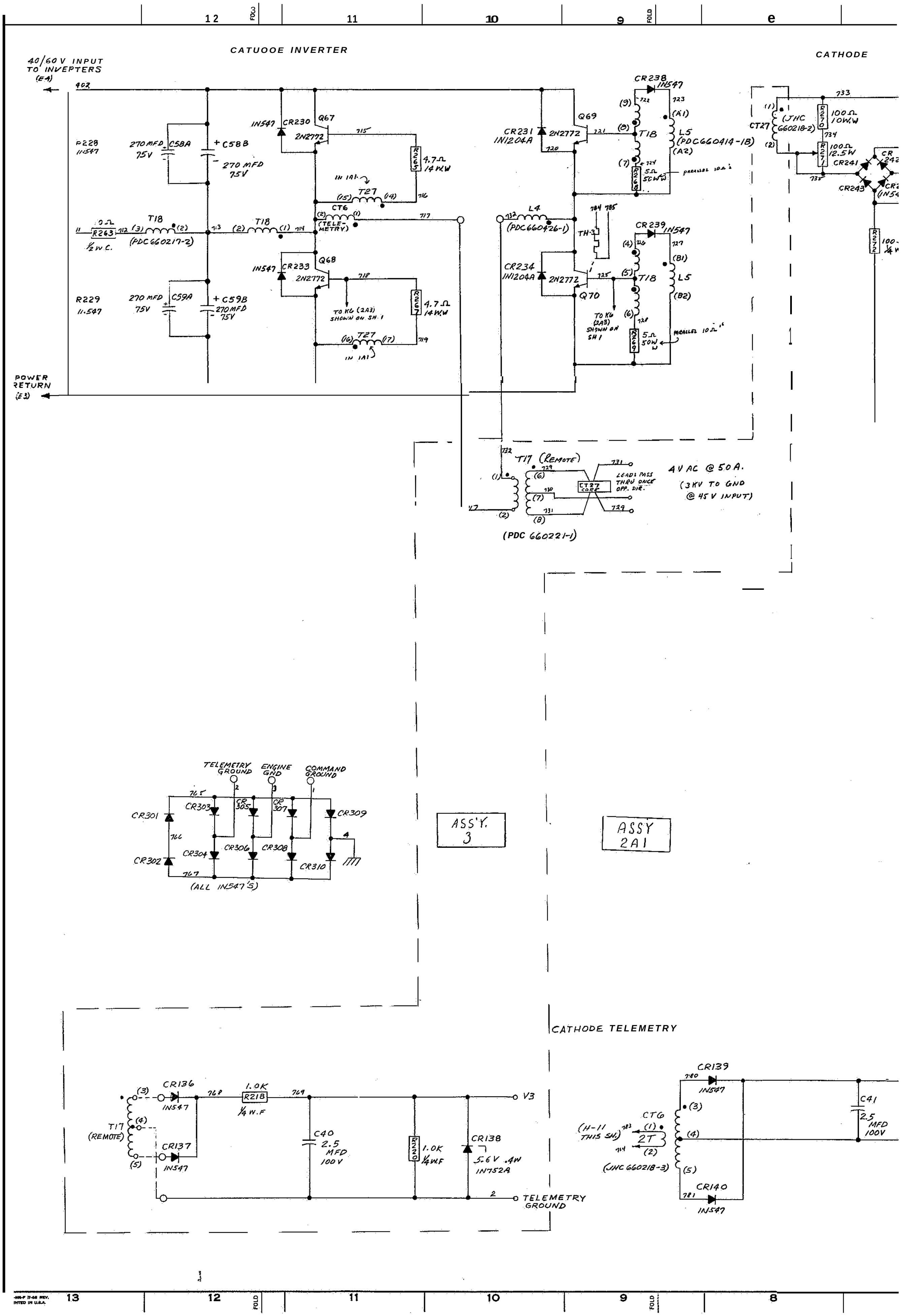
ELEMENTARY DIAGRAM
ION ENGINE POWER CONDITIONER
(H.V. RECTIFIERS – TELEMETRY)

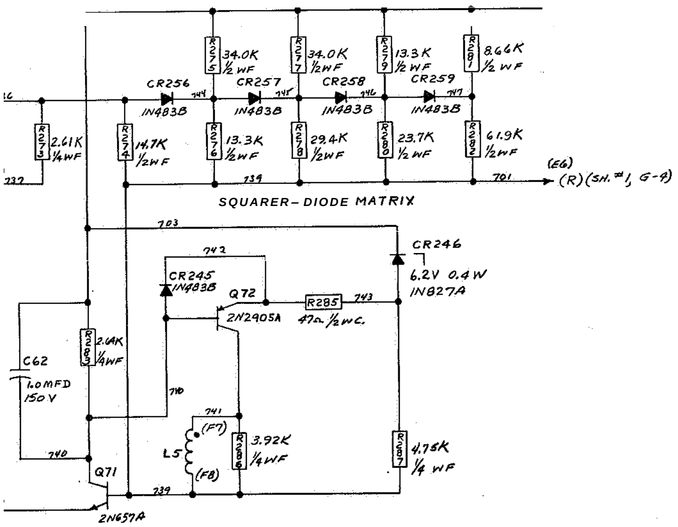
SIZE	CODE IDENT NO.	
F	01526	44F242512

SCALE | SHEET 6 OF 8

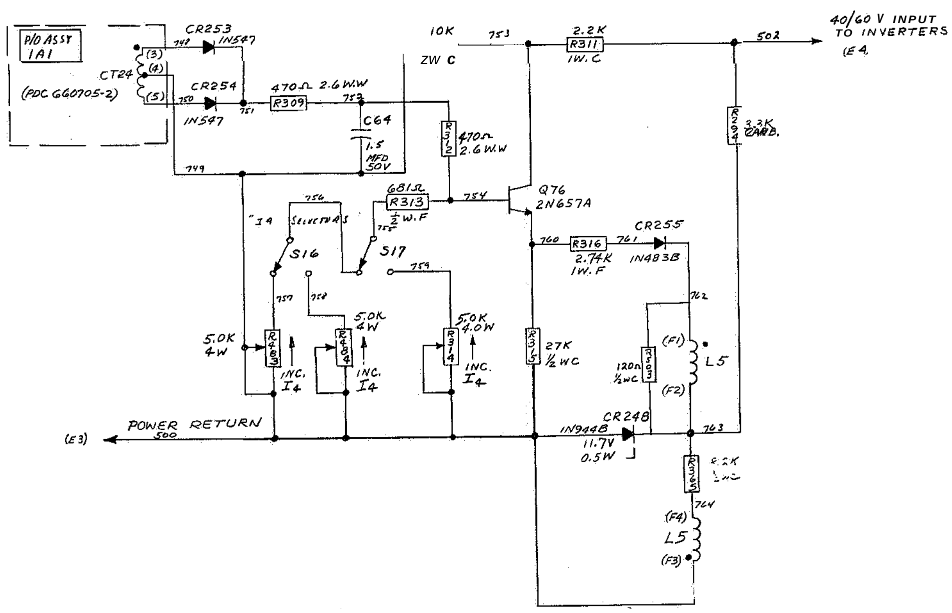
REV | 44F242512 | SIZE F

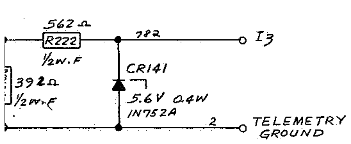
6 | 5 | 4 | 3 | 2 | 1


CATUOOE INVERTER
CATHODE
40/60 V INPUT TO INVEPTERS (E4)
POWER RETURN (E3)
R228
R229
C58A
C58B
270 MFD 75V
C59A
C59B
T18
R263
CR230
Q67
2N2772
R265
4.7Ω 14W.W
T27
CT6
CR233
Q68
R267
TO KG (2A3) SHOWN ON SH. 1
CR238
1N547
Q69
CR231
1N1204A
L5
(PDC660414-1B)
R268
5Ω 50W
L4
(PDC660426-1)
TH-3
CR239
CR234
Q70
R269
CT27
(JHC 660218-2)
R270
100Ω 10W.W
R271
100Ω 12.5W
CR241
CR243
R272
T17 (REMOTE)
(PDC 660221-1)
LEADS PASS THRU ONCE OPP. DIR.
4 V AC @ 50 A.
(3KV TO GND @ 45 V INPUT)
TELEMETRY GROUND
ENGINE GND
COMMAND GROUND
CR301
CR302
CR303
CR304
CR305
CR306
CR307
CR308
CR309
CR310
(ALL 1N547'S)
ASS'Y. 3
ASSY 2A1
CATHODE TELEMETRY
CR136
1N547
R218
1.0K 1/4 W.F
CR137
T17 (REMOTE)
C40
2.5 MFD 100 V
R220
1.0K 1/4 W.F
CR138
5.6 V .4W 1N752A
V3
TELEMETRY GROUND
CR139
CR140
CT6
2T
(H-11 THIS SH)
(JHC 660218-3)
C41
2.5 MFD 100V



ANODE CONTROL OF CATHODE CURRENT





UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES— TOLERANCES ON: 2-PLACE DECIMALS ± 3-PLACE DECIMALS ± ANGLES ± FRACTIONS ±	ALL SURF ✓	
MATERIAL—		

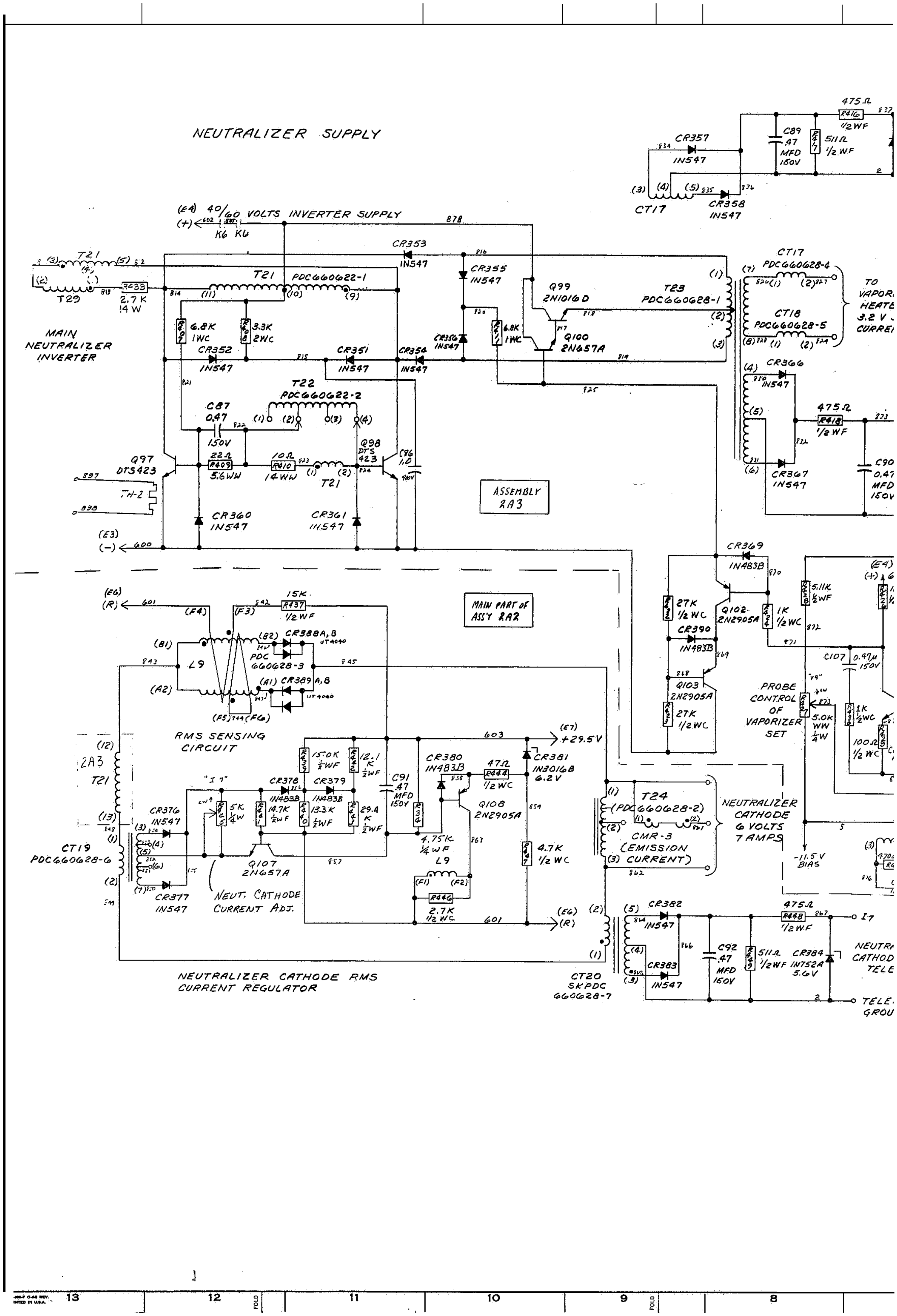
SIGNATURES	DAY	MO	YR
DRAWN Elliott	12	4	66
CHECKED			
ISSUED			
ENGRG P.D. Corey	19	12	66
MFG			
MATLS			

3S2020BM121A1

GENERAL ELECTRIC
SPECIALTY CONTROL DEPT LOC WAYNESBORO, VA.

ELEMENTARY DIAGRAM
ION ENGINE POWER CONDITIONER
(CATHODE SUPPLY)

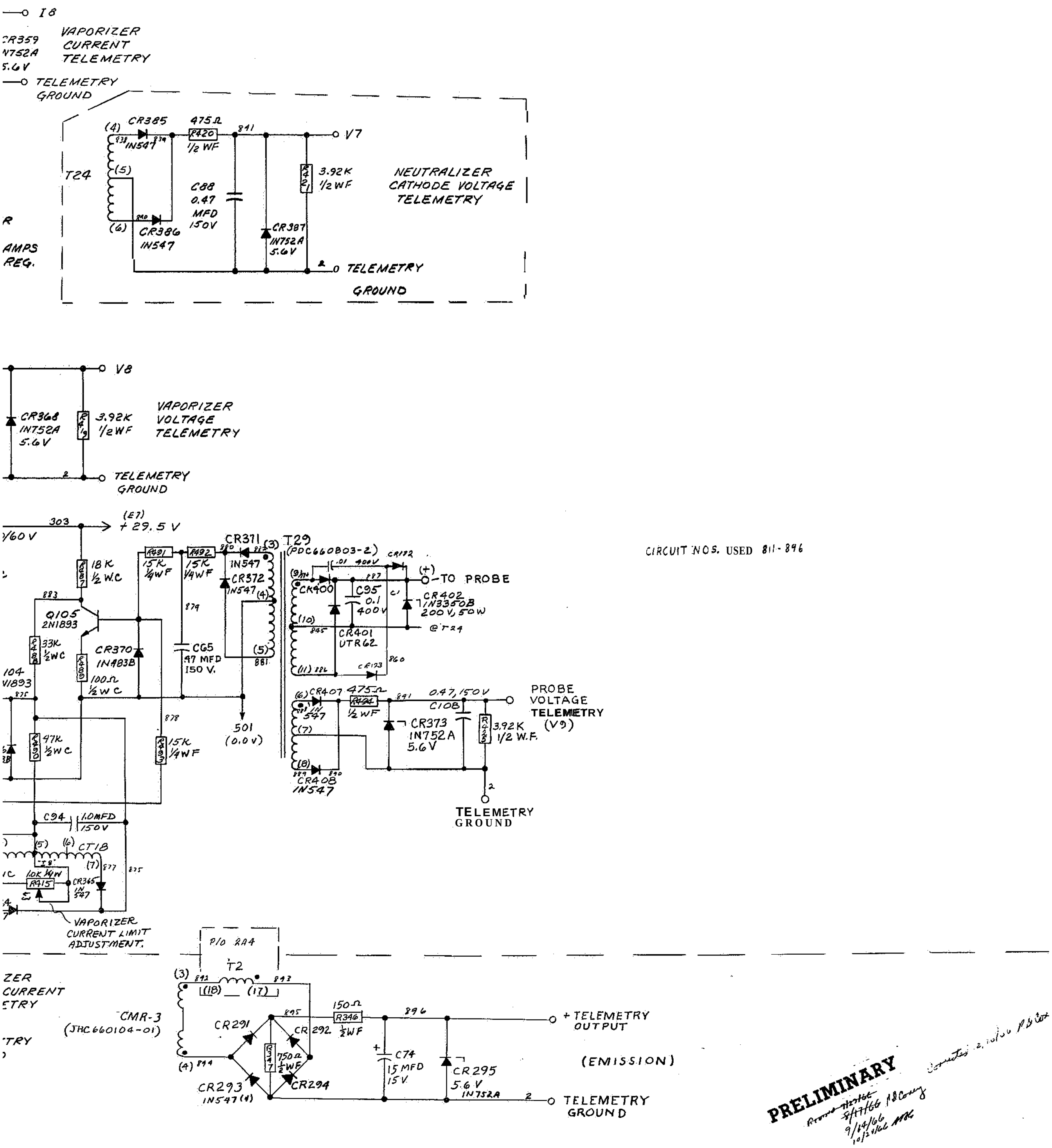
SIZE	CODE IDENT NO.	
F	01526	44F242512
SCALE		SHEET 7 OF 8


NEUTRALIZER SUPPLY
(E4) 40/60 VOLTS INVERTER SUPPLY
(+)
K6 K6
878
CR353 1N547
CR355 1N547
Q99 2N1016D
T23 PDC660628-1
CT17 PDC660628-4
CT18 PDC660628-5
TO VAPOR. HEATE 3.2 V CURRE
T21 PDC660622-1
T29
R433 2.7 K 14 W
MAIN NEUTRALIZER INVERTER
R407 6.8K 1WC
R408 3.3K 2WC
CR352 1N547
CR351 1N547
CR354 1N547
CR356 1N547
R411 6.8K 1WC
Q100 2N657A
T22 PDC660622-2
C87 0.47 150V
R409 22Ω 5.6WW
R410 10Ω 14WW
Q97 DTS423
Q98 DTS 423
C96 1.0 400V
TH-2
CR360 1N547
CR361 1N547
ASSEMBLY 2A3
(E3) (-)
CR357 1N547
CR358 1N547
CT17
C89 .47 MFD 150V
R417 511Ω 1/2 WF
475Ω R416 1/2 WF
CR366 1N547
CR367 1N547
475Ω R418 1/2 WF
C90 0.47 MFD 150V
MAIN PART OF ASS'Y 2A2
(E6) (R)
15K R437 1/2 WF
L9
CR388A,B UT4040
PDC 660628-3
CR389A,B UT4040
RMS SENSING CIRCUIT
2A3 T21
CT19 PDC660628-6
CR376 1N547
CR377 1N547
"I 7"
R445 5K 1/4 W
R441 14.7K 1/2 WF
CR378 1N483B
CR379 1N483B
R440 13.3K 1/2 WF
R439 15.0K 1/2 WF
R442 12.1 K 1/2 WF
R443 29.4 K 1/2 WF
C91 .47 MFD 150V
Q107 2N657A
NEUT. CATHODE CURRENT ADJ.
R438 4.75K 1/4 WF
CR380 1N483B
47Ω R444 1/2 WC
Q108 2N2905A
CR381 1N3016B 6.2V
(E7) +29.5V
R447 4.7K 1/2 WC
R446 2.7K 1/2 WC
(E6) (R)
NEUTRALIZER CATHODE RMS CURRENT REGULATOR
CT20 SKPDC 660628-7
CR369 1N483B
R432 27K 1/2 WC
CR390 1N483B
Q102 2N2905A
R434 1K 1/2 WC
R435 5.11K 1/2 WF
Q103 2N2905A
R433 27K 1/2 WC
C107 0.47μ 150V
PROBE CONTROL OF VAPORIZER SET
R427 5.0K WW 1/4W
1K 1/2 WC
100Ω 1/2 WC
T24 (PDC660628-2)
CMR-3 (EMISSION CURRENT)
NEUTRALIZER CATHODE 6 VOLTS 7 AMPS
-11.5 V BIAS
CR382 1N547
CR383 1N547
C92 .47 MFD 150V
R449 511Ω 1/2 WF
475Ω R448 1/2 WF
CR384 1N752A 5.6V
I7
NEUTR CATHOD TELE
TELE GROU
13
12
11
10
9
8

REV	44F242512	SIZE F

REVISIONS

ZONE	LTR	DESCRIPTION	DATE	APPROVED



CIRCUIT NOS. USED 811-896

PRELIMINARY

Corrected 2/10/66 [illegible]

[illegible] 8/17/66 P.D. Coney

9/14/66

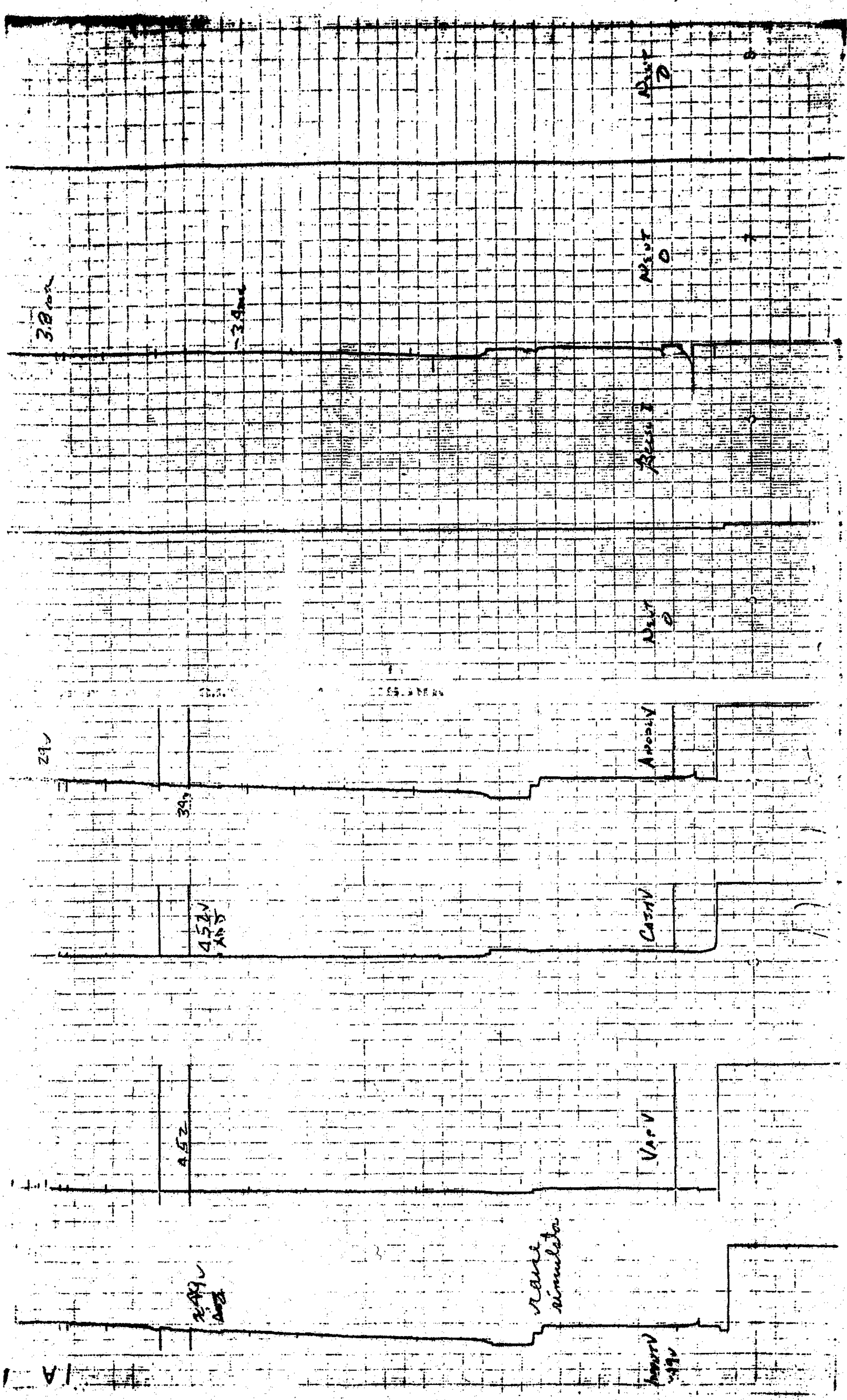
10/21/66 [illegible]

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES— TOLERANCES ON: 2-PLACE DECIMALS ± 3-PLACE DECIMALS ± ANGLES ± FRACTIONS ± ALL SURF ✓ MATERIAL—	SIGNATURES	DAY	MO	YR	GENERAL ELECTRIC SPECIALTY CONTROL DEPT LOC WAYNESBORO, VA.
	DRAWN [signature]	30	6	66	ELEMENTARY DIAGRAM
	CHECKED				ION ENGINE POWER CONDITIONER
	ISSUED				(NEUTRALIZER SUPPLY)
	ENGRG P.D. Coney	19	12	66	
	MFG				
	MATLS				
	3S2020BM121A1				SIZE F · CODE IDENT NO. 01526 · 44F242512
					SCALE · SHEET 8 OF 8

APPENDIX C

This appendix contains strip-chart recordings reproduced from power conditioner/ion thrustor tests at INW, NASA-LeRC and at TRW, Inc. Redondo Beach, California.

4-1A



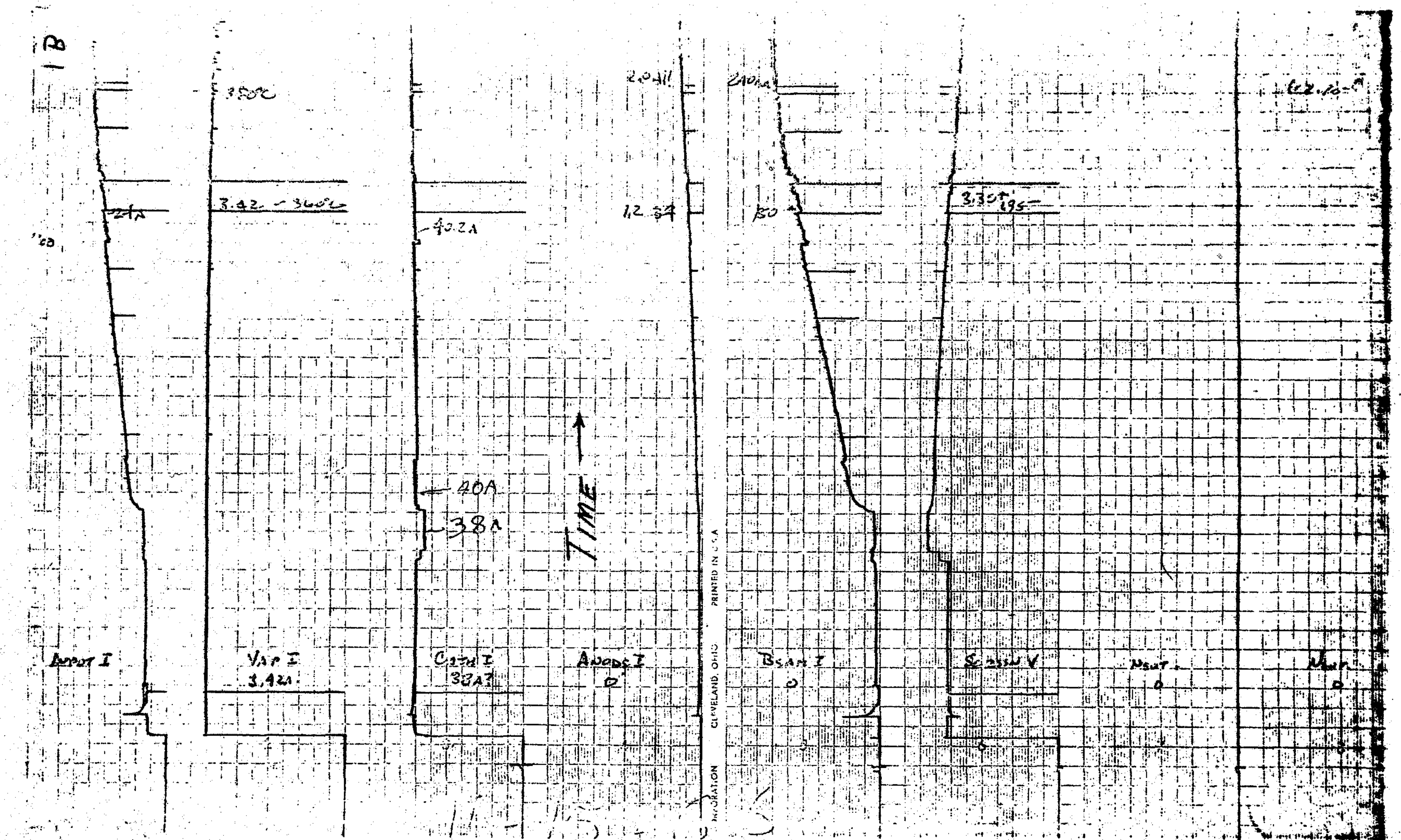
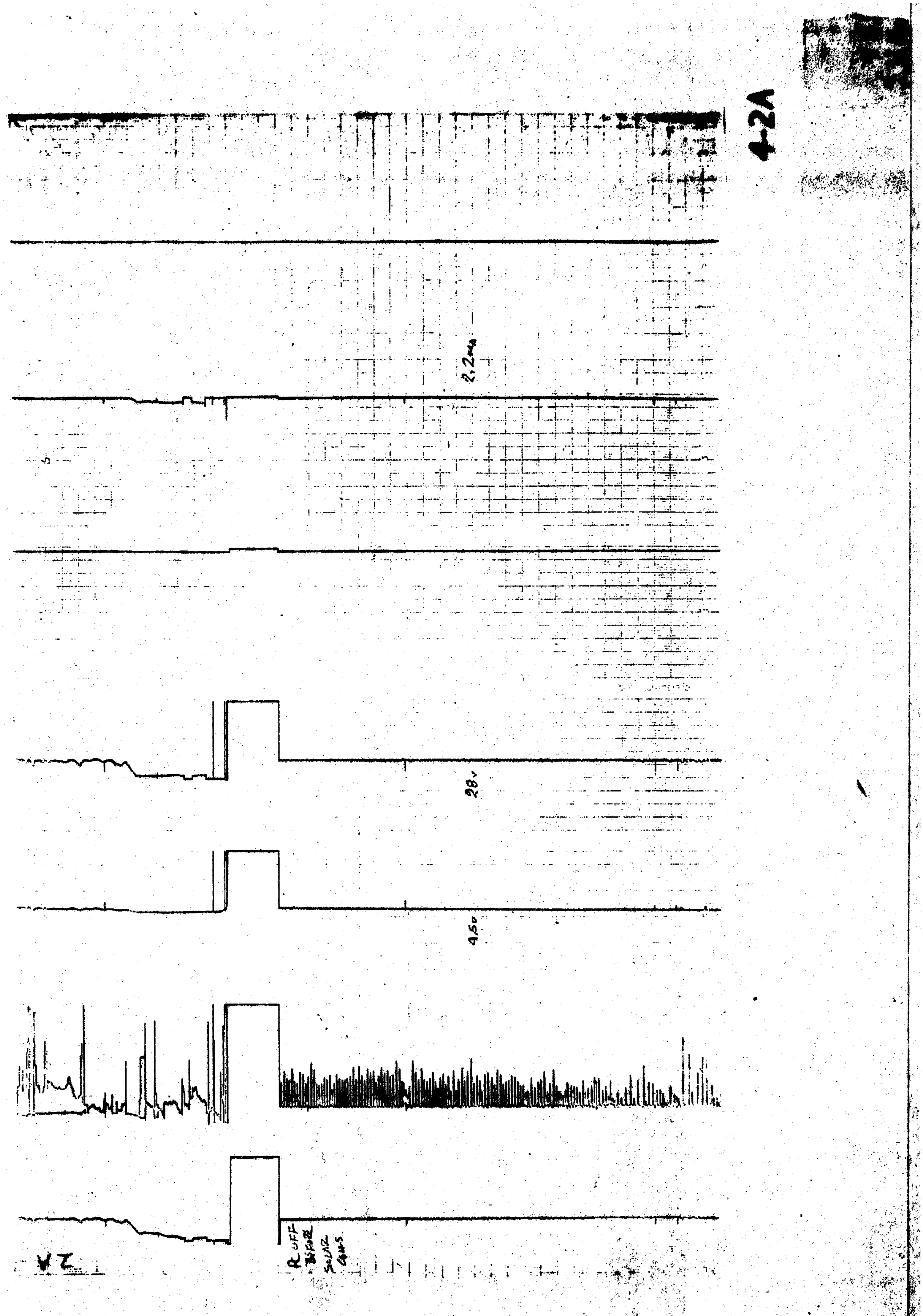

TIME
40A
38A
Vap I
3.42A
Cath I
Anode I
0
Beam I
0
Screen V
PRINTED IN U.S.A.
CLEVELAND, OHIO

FIGURE 4-1B


4-2A
2.2ma
28v
450

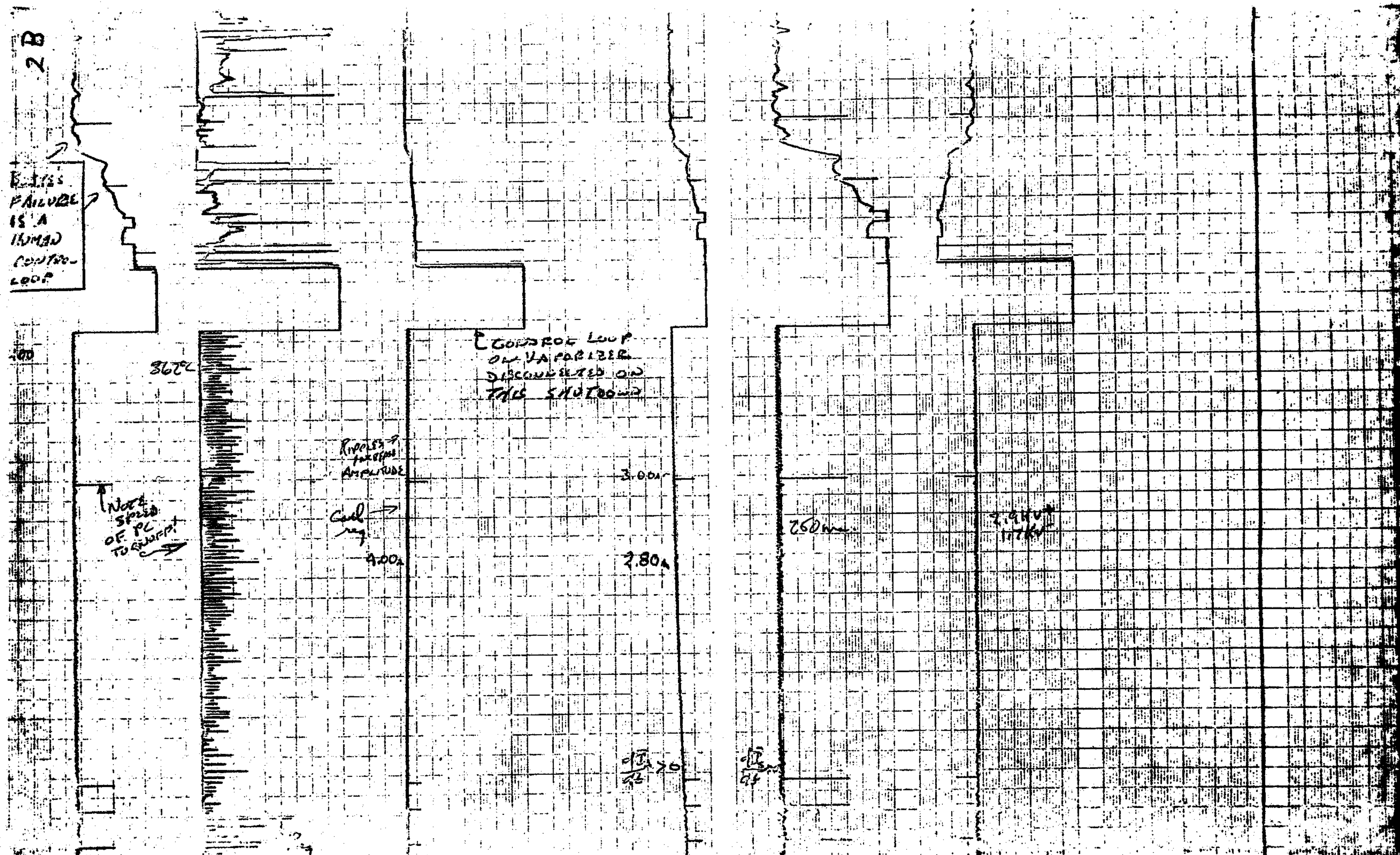
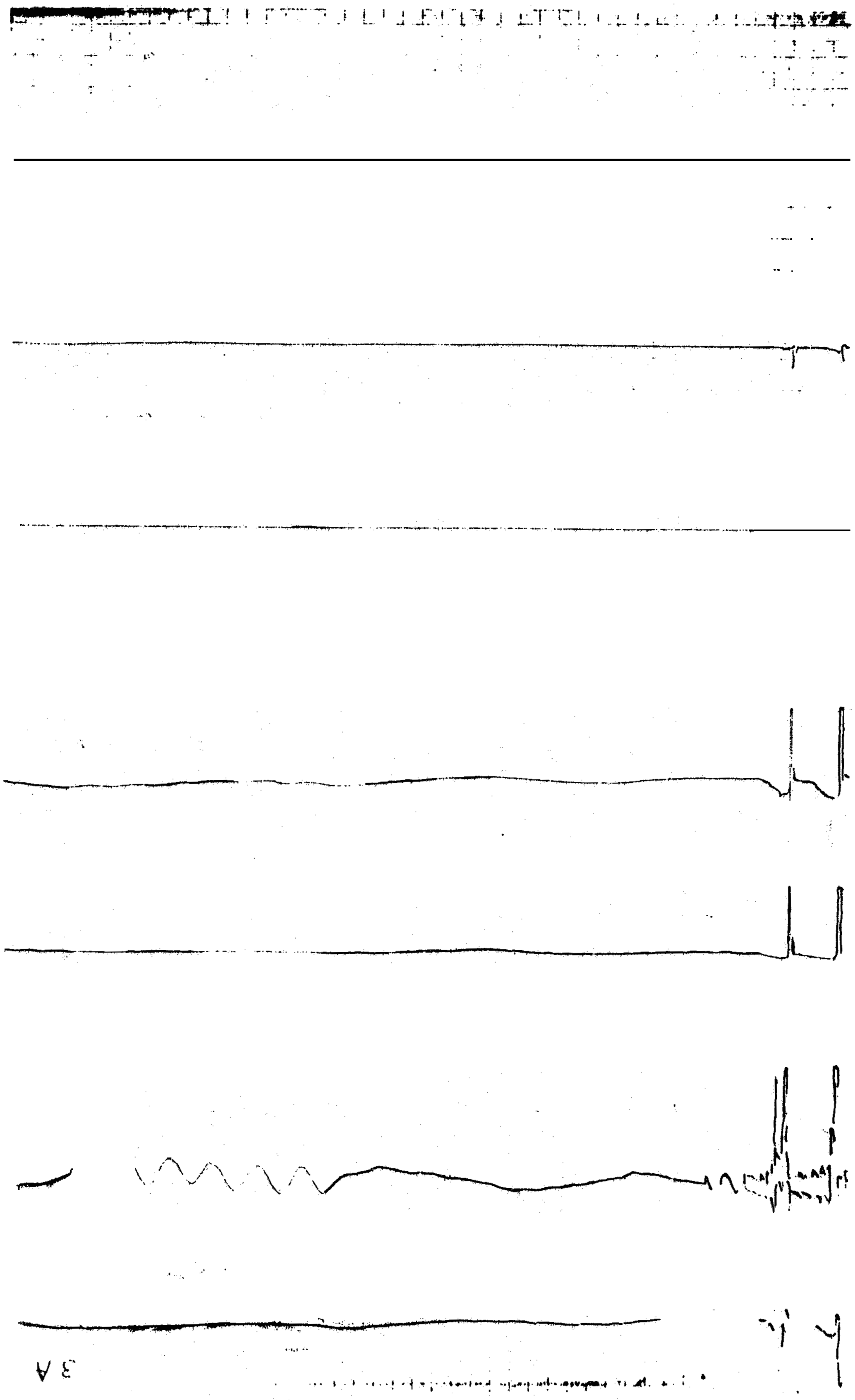

2B
FAILURE
IS A
HUMAN
CONTROL
LOOP
362°C
NOTE
SPEED
OF PC
TURNOFF
CONTROL LOOP
ON VAPORIZER
DISCONNECTED ON
THIS SHUTDOWN
3.00A
4.00A
2.80A
260mA

FIGURE 4 2B

e-3A



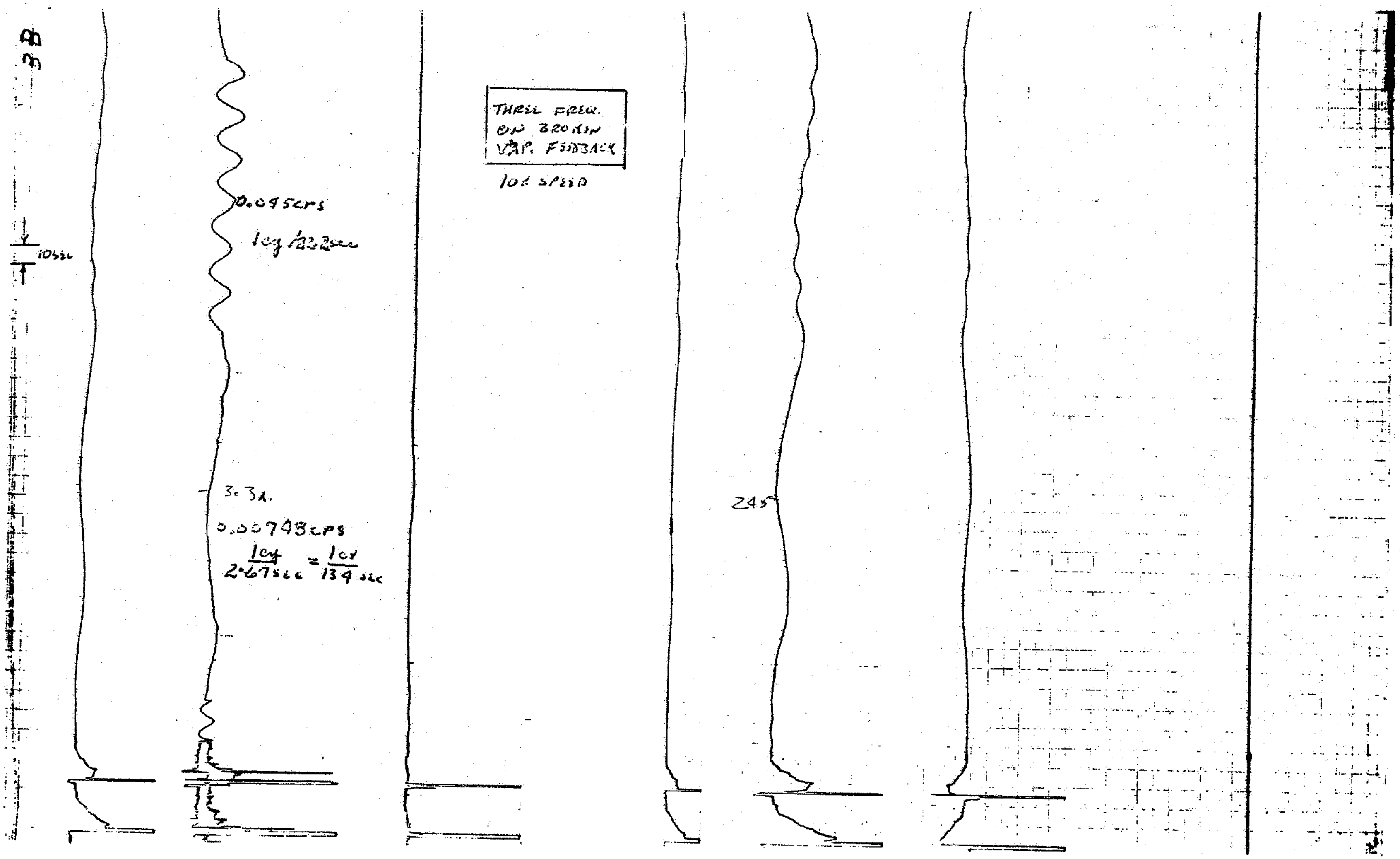
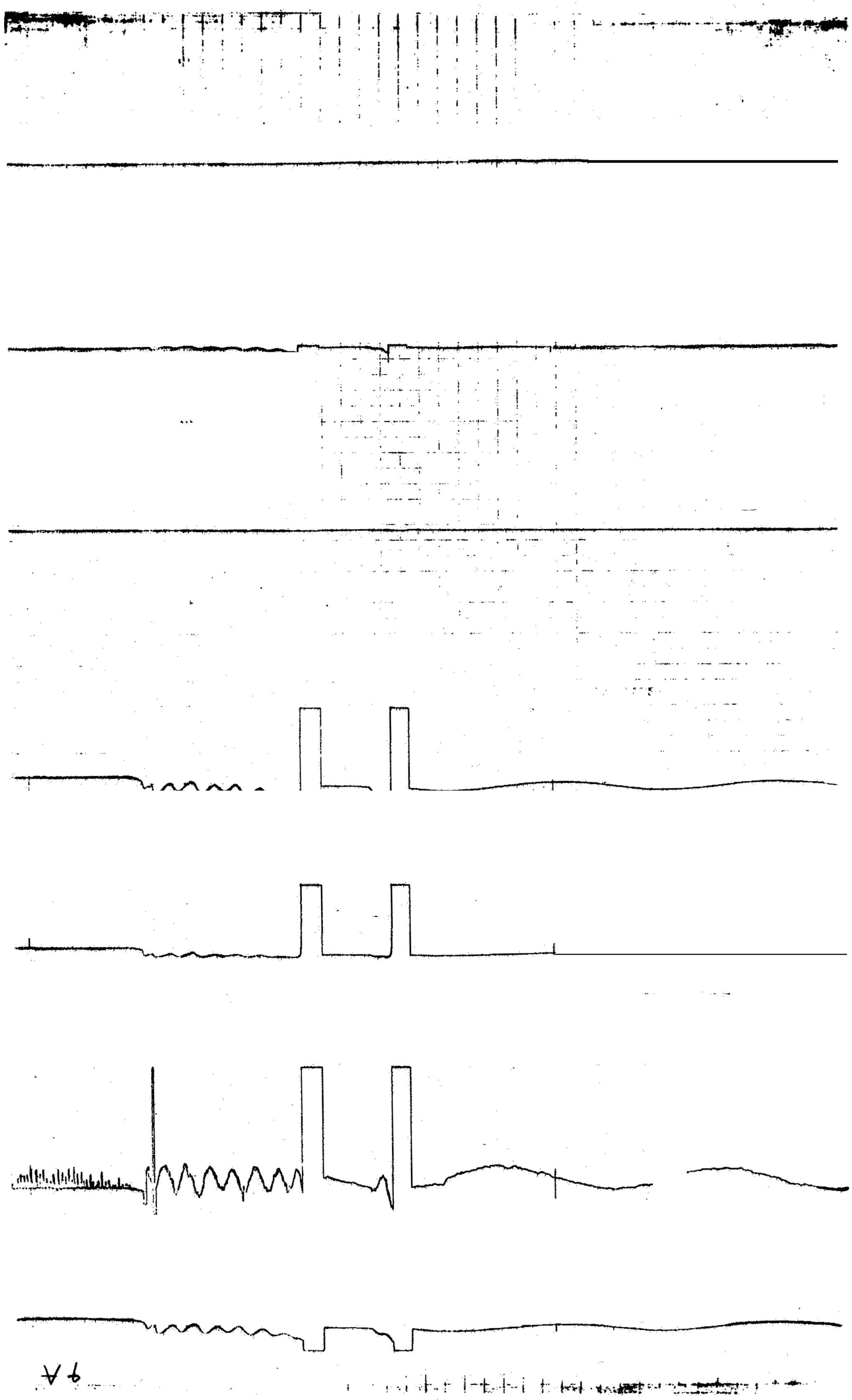

THREE FREQ.
ON BROKEN
VAP. FEEDBACK
10x SPEED
0.095cps
3.3x
0.00743cps
24s
10sec

FIGURE 4-3B



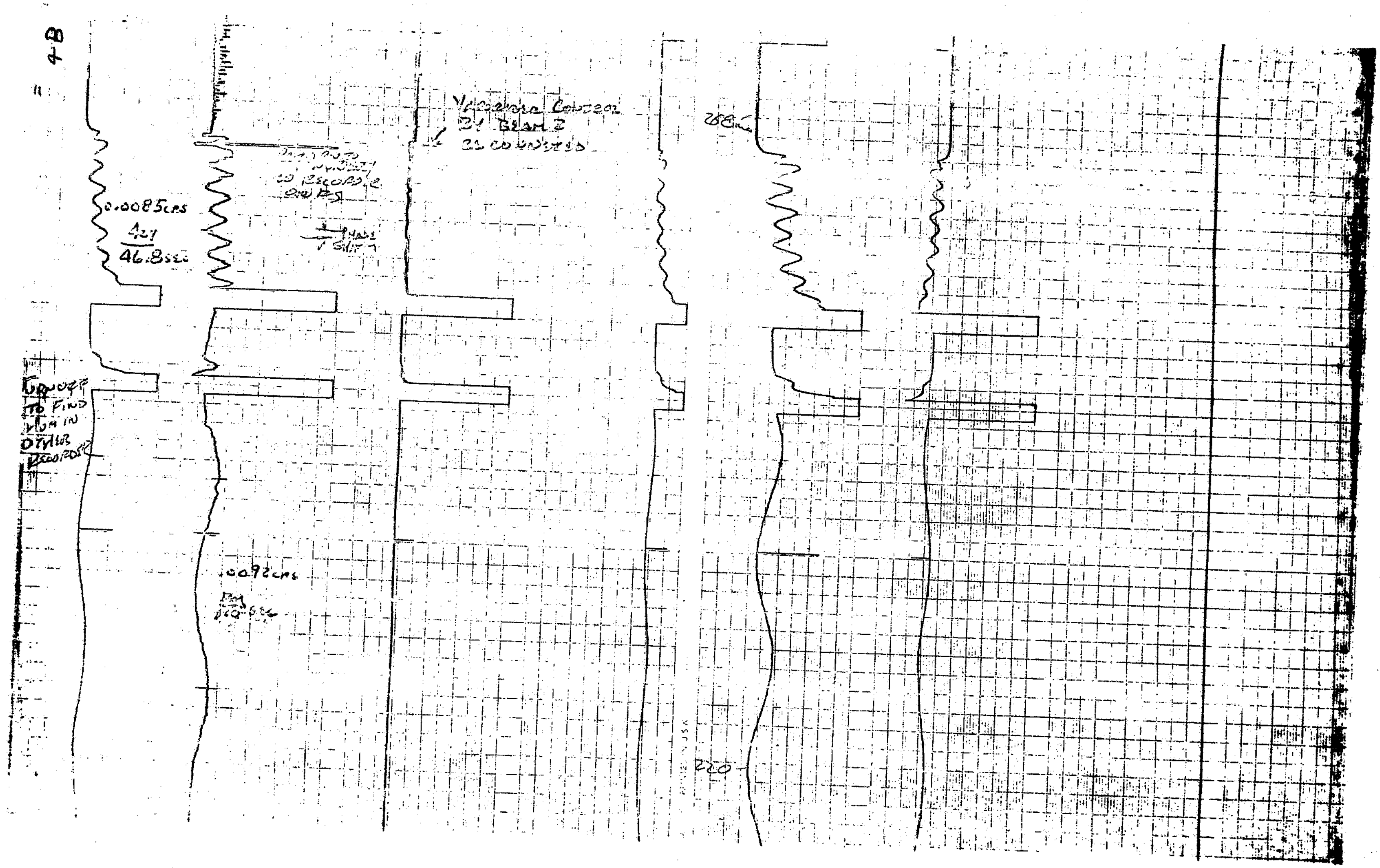
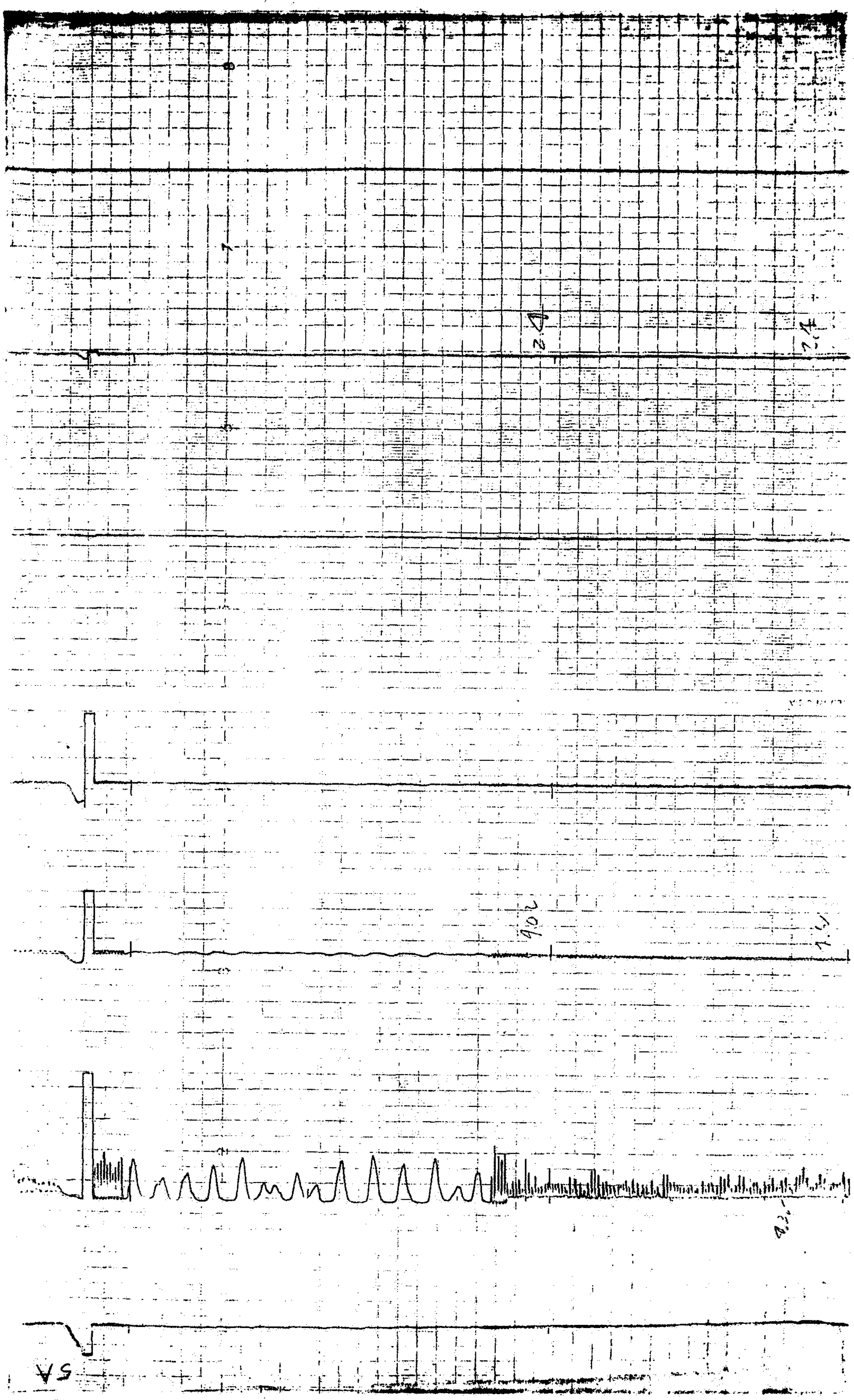


FIGURE 4-4B



4-5A

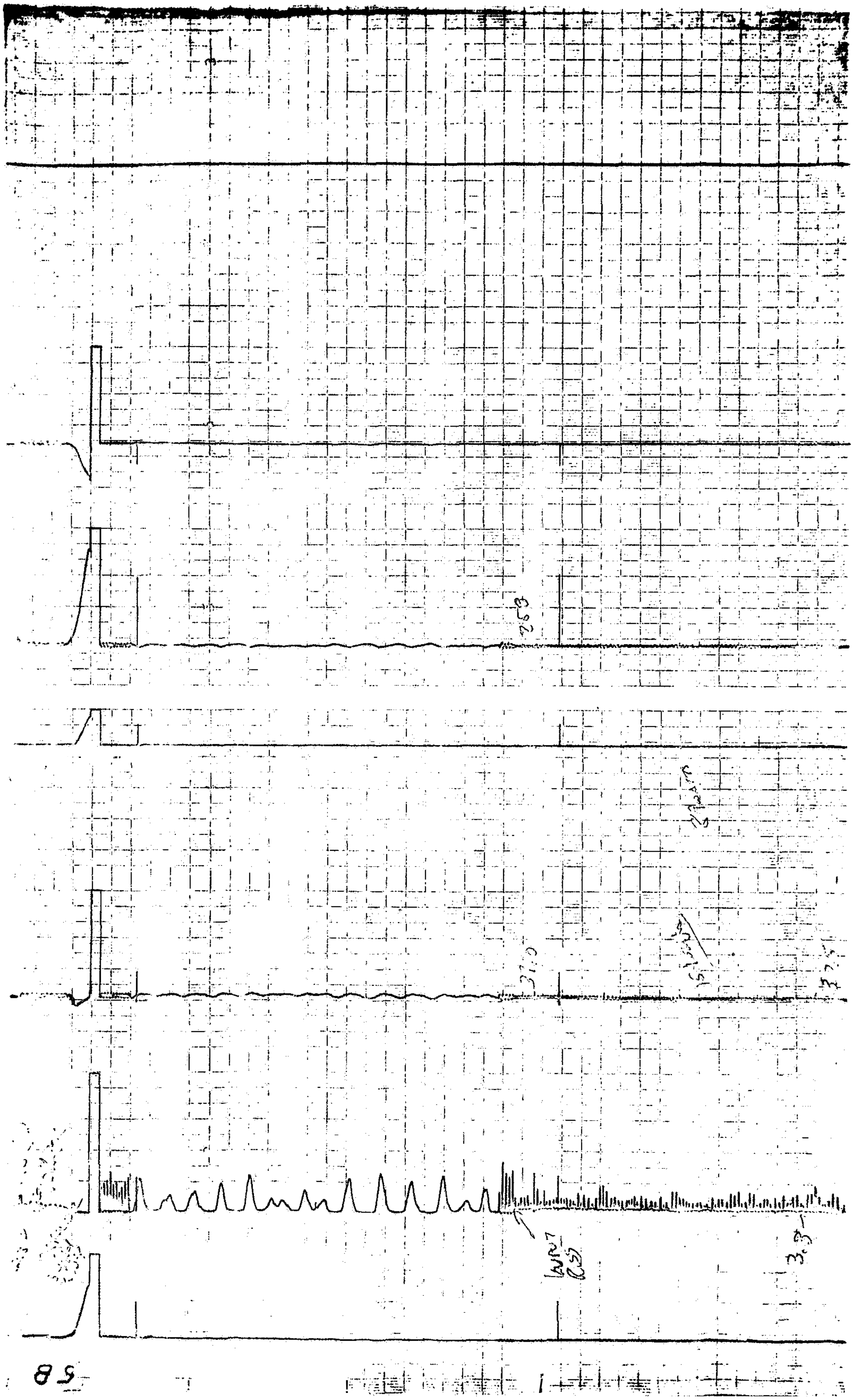
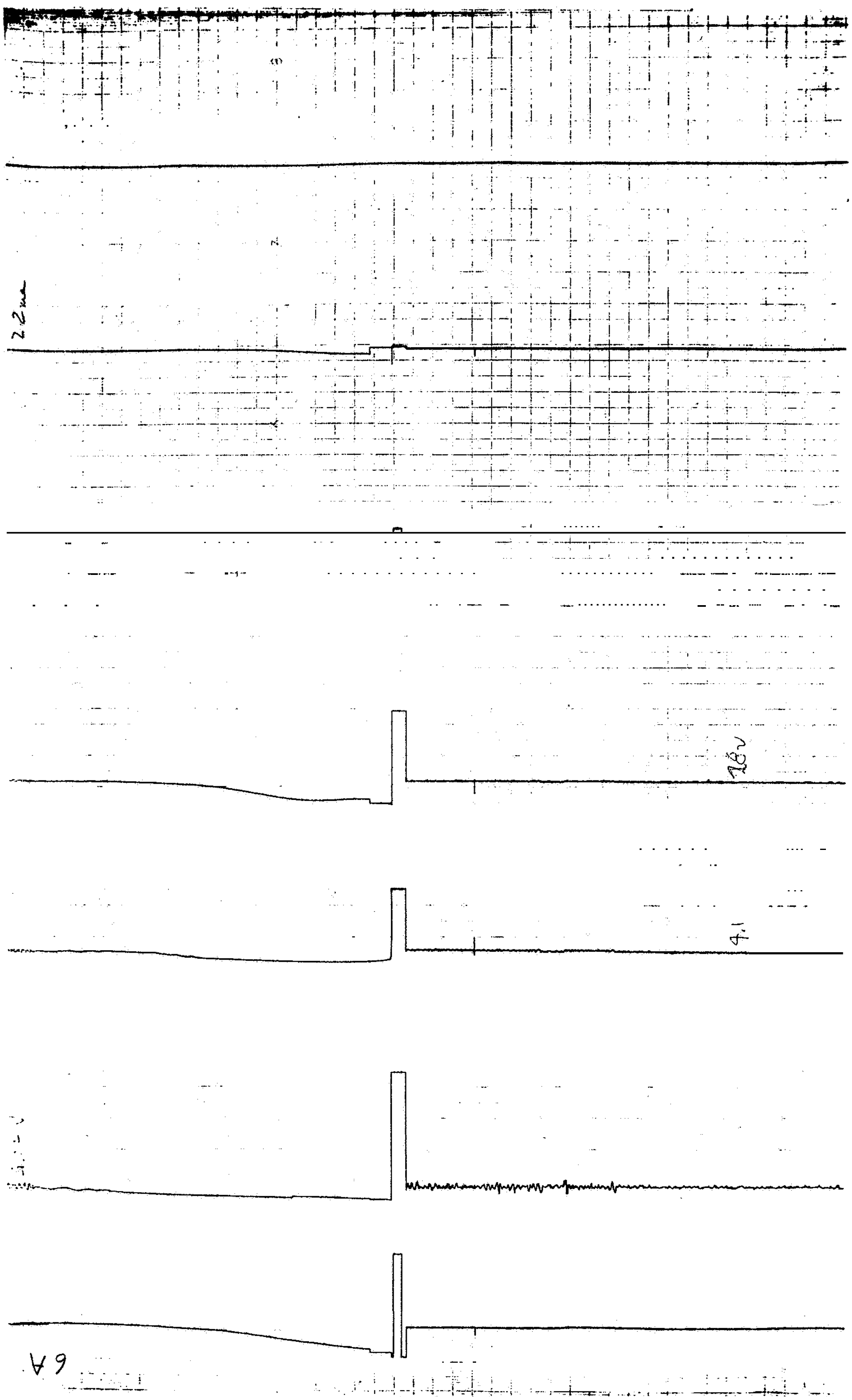


FIGURE 4-5B



4-6A

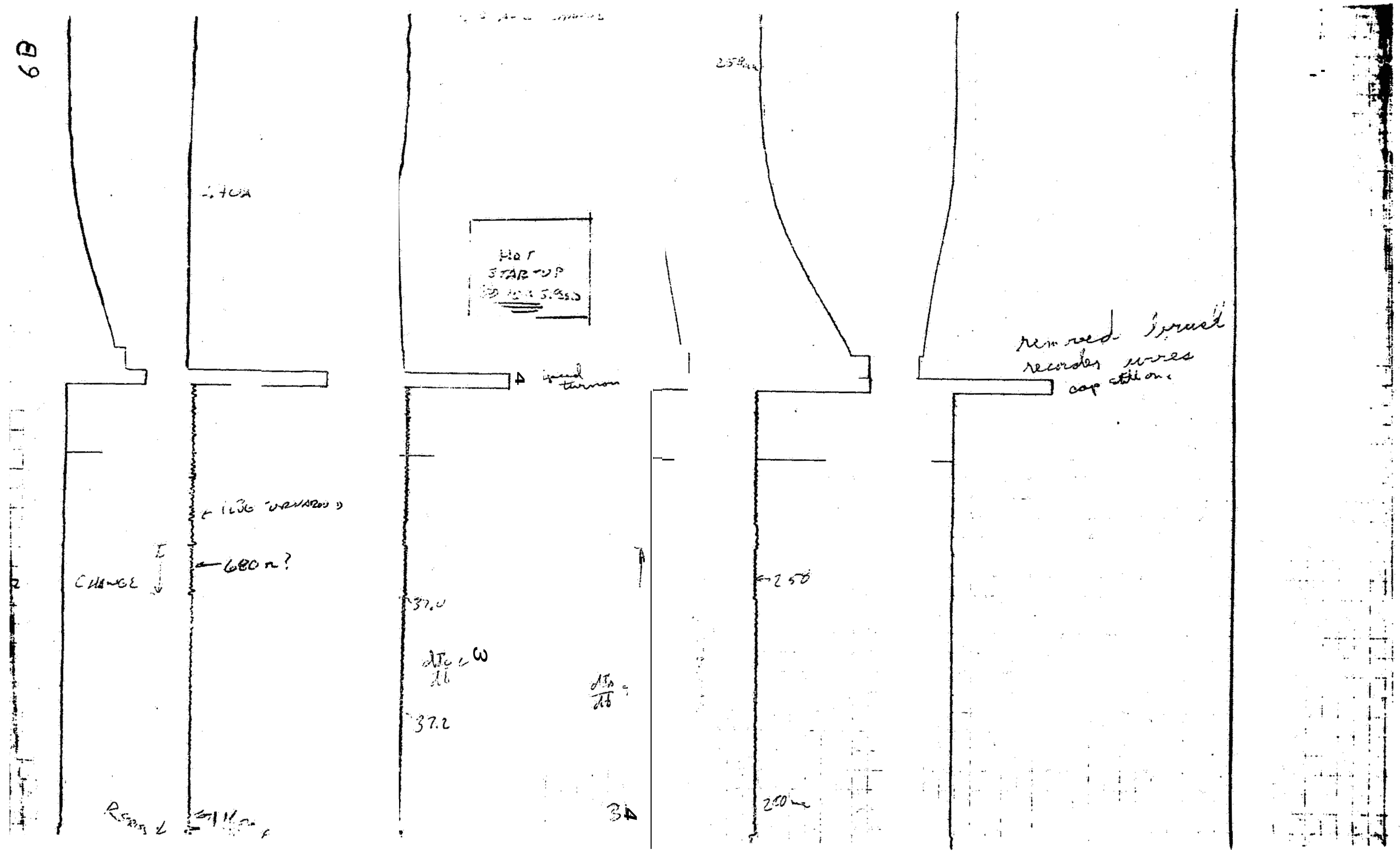
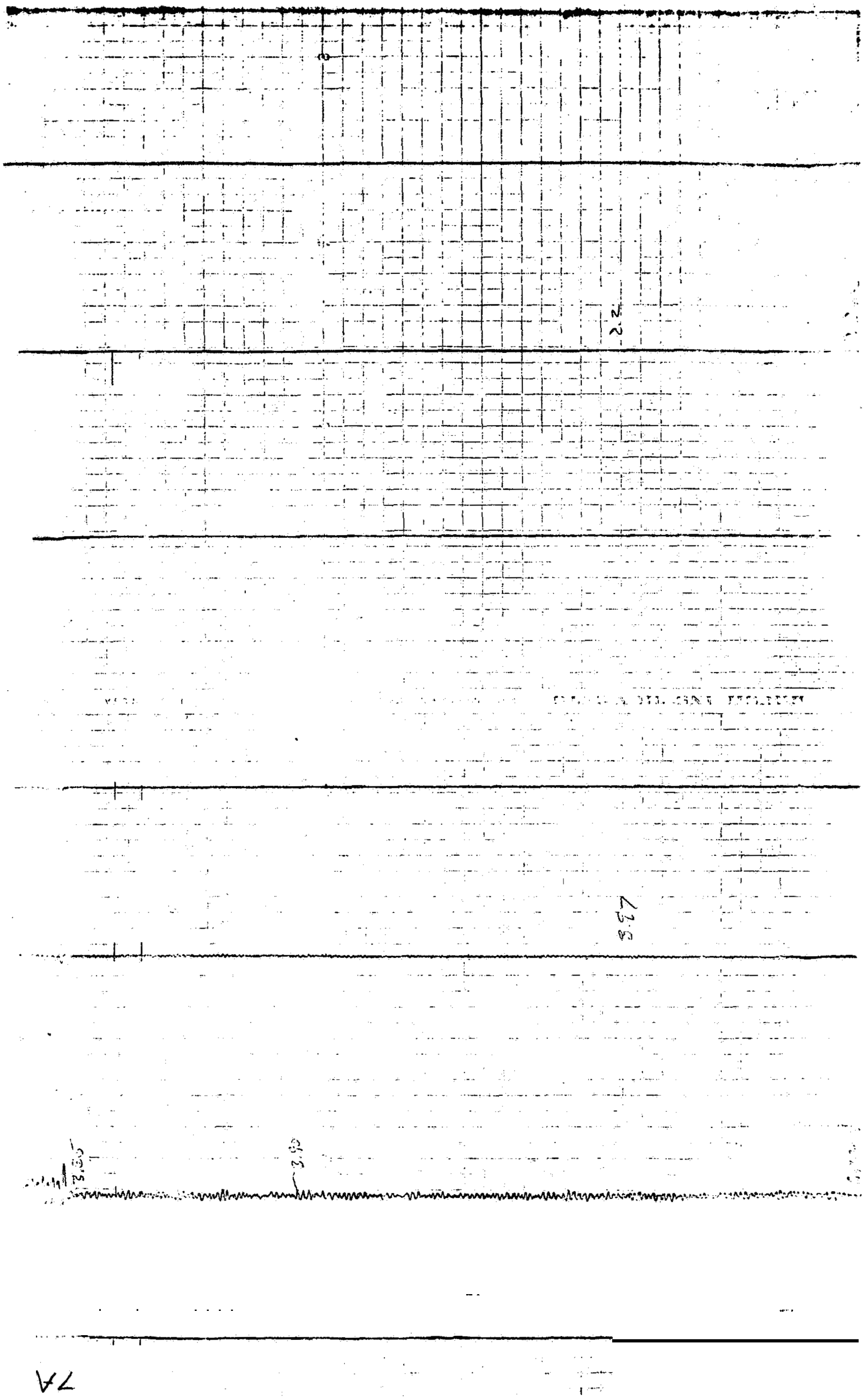

6B
HOT START-UP
CHANGE
680 n?
37.0
37.2
2.50
removed Brush recorder wires

FIGURE 4-6B



4-7A

7A

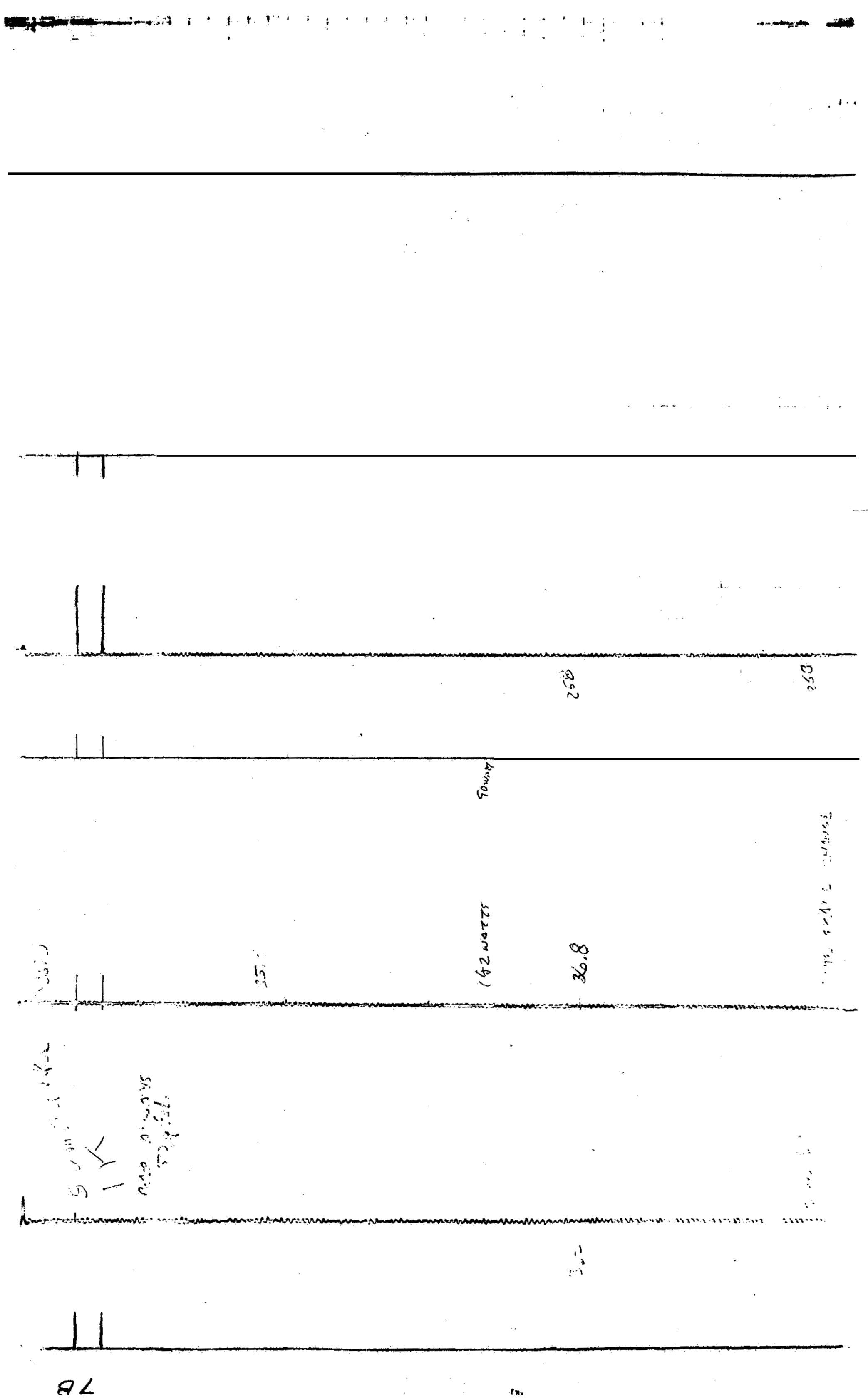
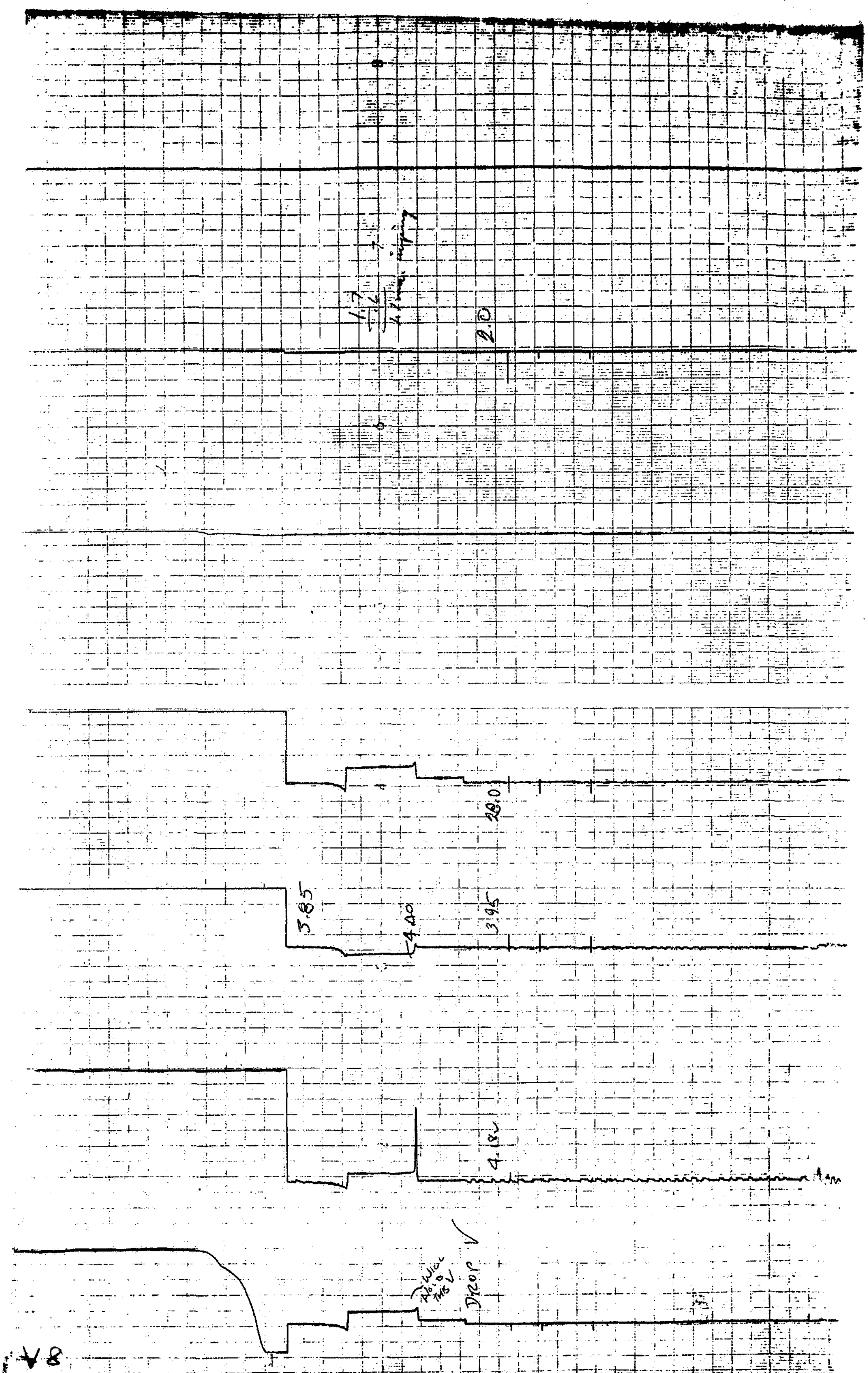


FIGURE 4-7B

4-8A



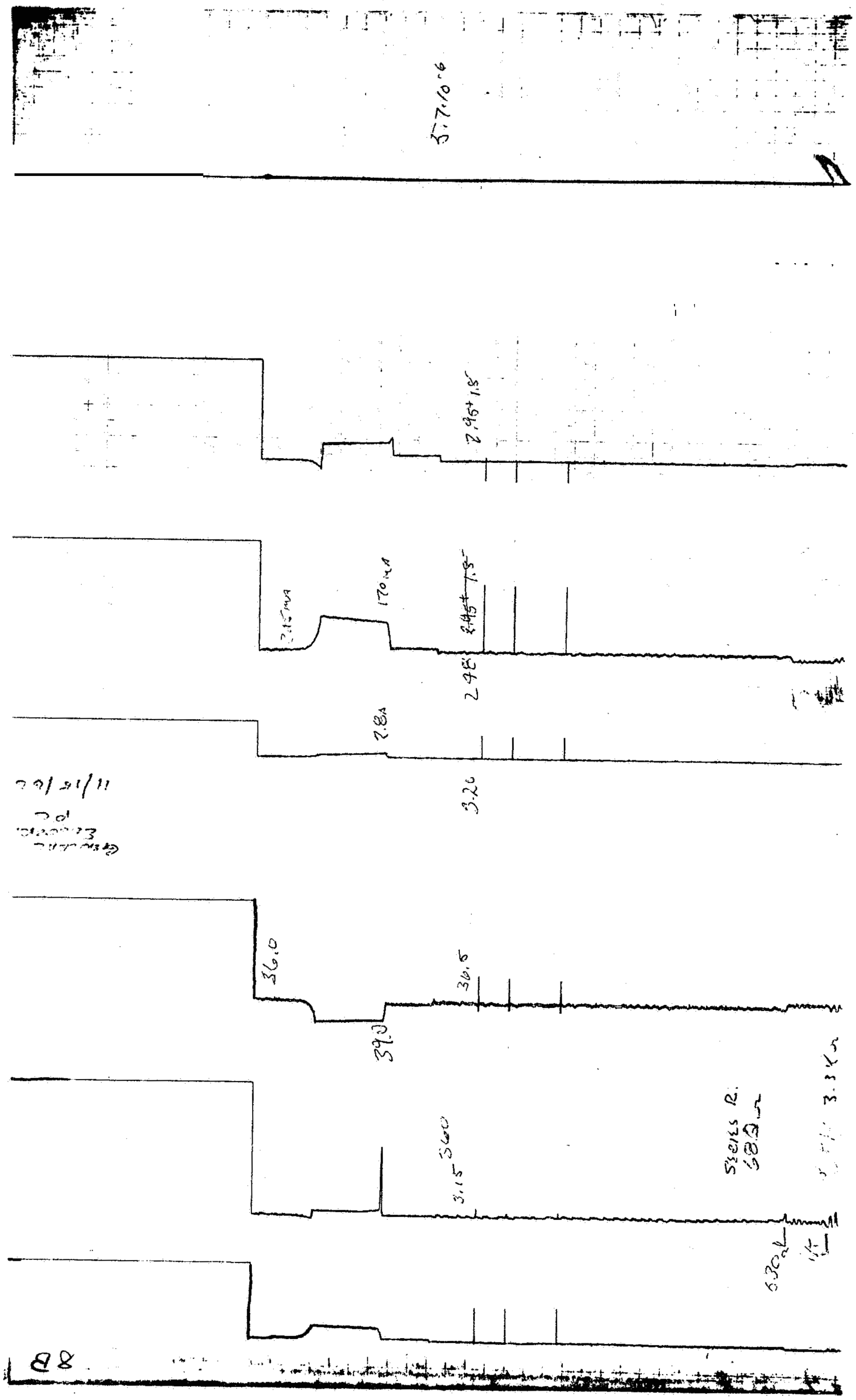


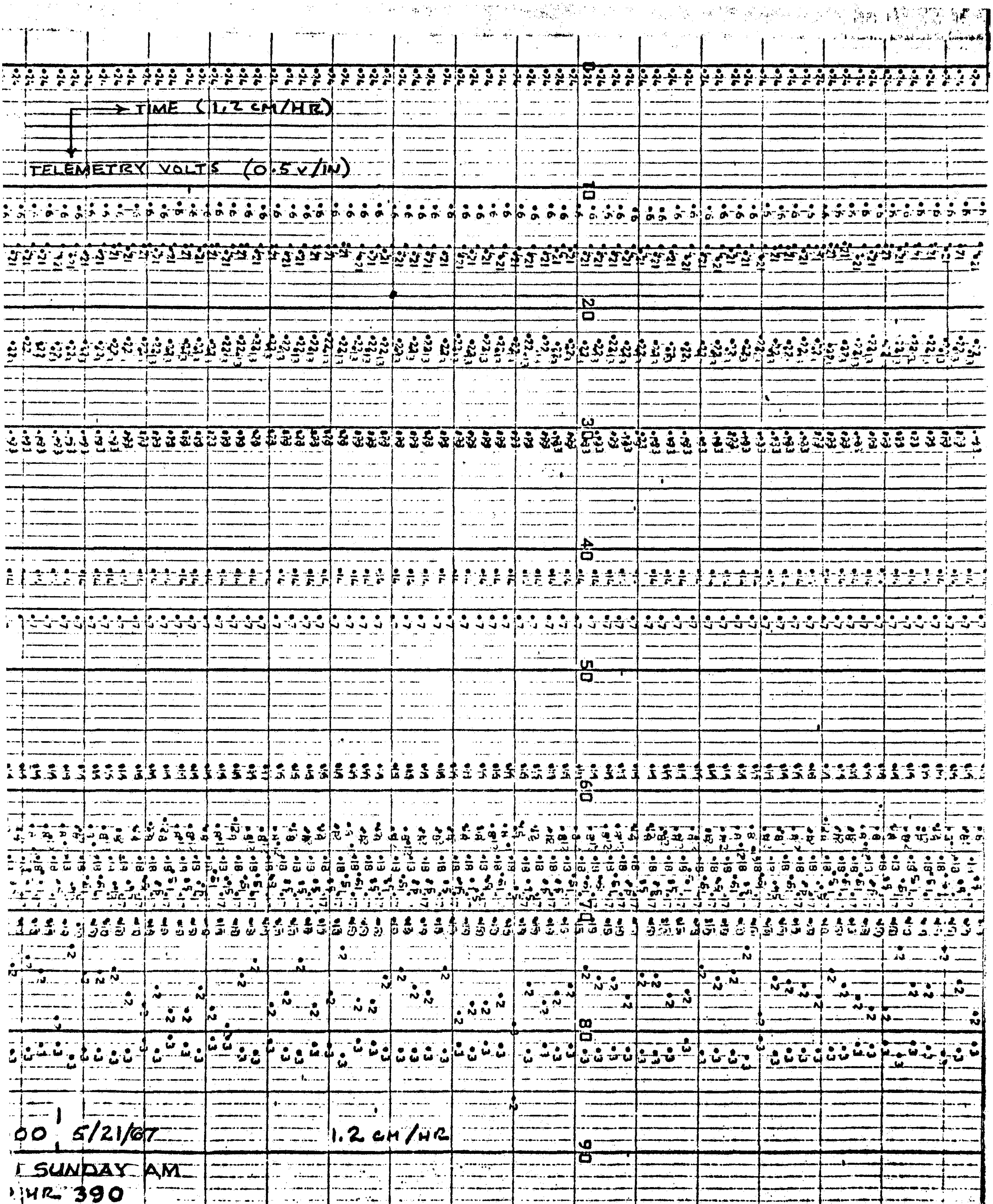
FIGURE 4-8B

BY .... DATE .... SUBJECT .... SHEET NO. .... OF ....

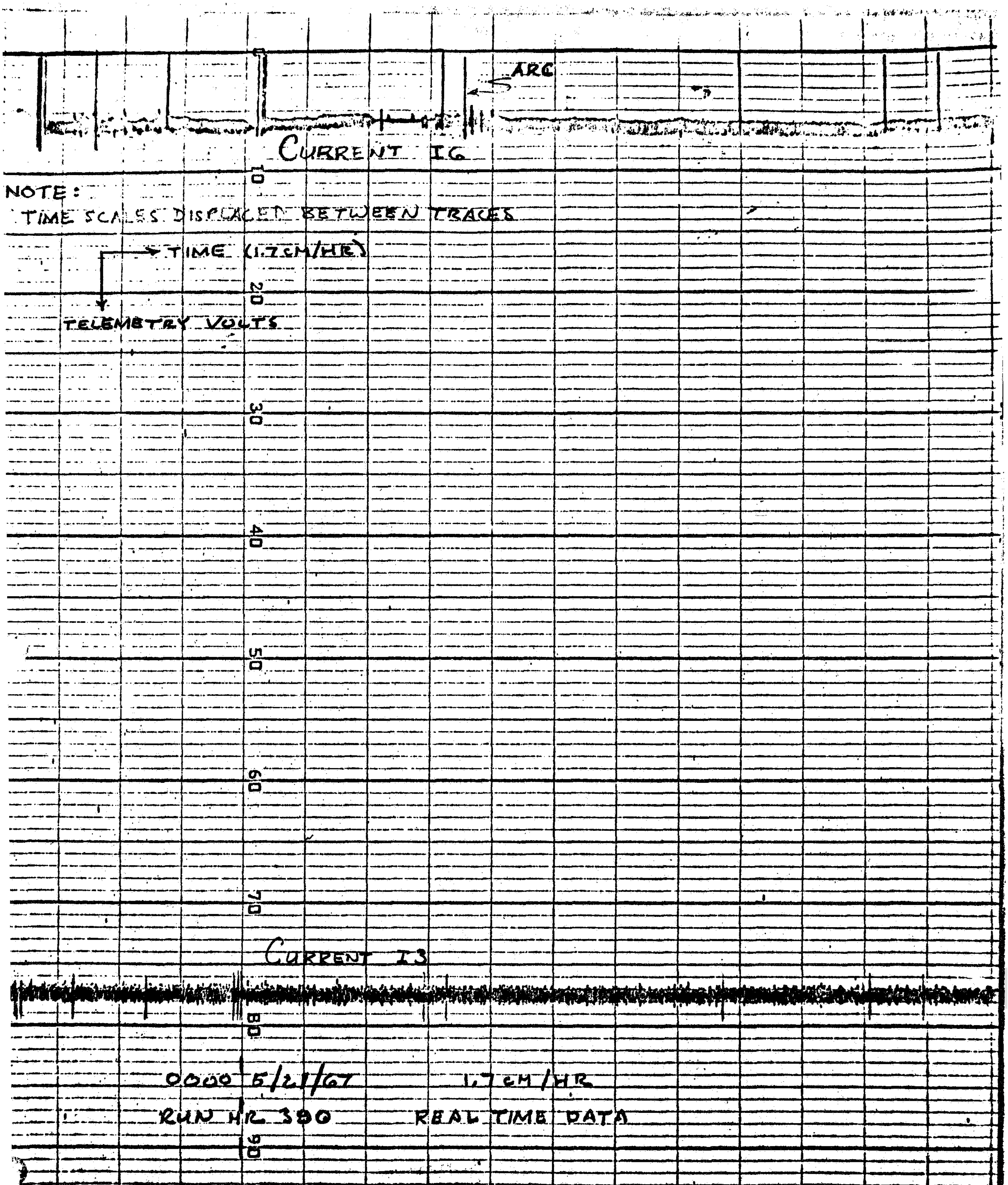
CHKD. BY ..... DATE .... JOB NO. ....

CORRESPONDENCE TABLE FOR SAMPLED TELEMETRY.

POINT	PC NUMBER	NAME
1	–	INPUT CURRENT
2	I 2	VAPORIZER CURRENT
3	I 3	CATHODE CURRENT
4	I 4	ANODE CURRENT
5	I 5	POSITIVE HV CURRENT ('SCREEN')
6	I 6	NEGATIVE HV CURRENT ('ACCELERATOR')
7	I 7	NEUTRALIZER CATHODE CURRENT
8	I 8	NEUTRALIZER VAPORIZER CURRENT
9	–	NOT USED
10	–	NEUTRALIZER EMISSION CURRENT
11	V 1	INPUT VOLTAGE
12	V 2	VAPORIZER VOLTAGE
13	V 3	CATHODE VOLTAGE
14	V 4	ANODE VOLTAGE
15	V 5	POSITIVE HIGH VOLTAGE
16	V 6	NEGATIVE HIGH VOLTAGE
17	V 7	NEUTRALIZER CATHODE VOLTAGE
18	V 8	NEUTRALIZER VAPORIZER VOLTAGE
19	V 9	NEUTRALIZER ANODE VOLTAGE
20	–	NOT USED
21	–	TEMPERATURE OF PC
22	–	TEMPERATURE OF PC
23	–	TEMPERATURE OF PC
24	–	PRINT CYCLE SWITCH OFF



LIFE TEST CONSOLE TELEMETRY PRINT OUT SHOWING 14 HOURS STABLE UNATTENDED OPERATION SUNDAY, MAY 21. THE TEST BEGAN 1750 MAY 4 AND RAN CONTINUOUSLY UNTIL ION THRUSTOR FAILURE AT 1735 MAY 27.



LIFE TEST CONSOLE PRINT OUT SHOWING REAL TIME TELEMETRY. ION THRUSTOR ARC RATE OF APPROXIMATELY 1/HR. OCCURS DURING THESE 9 HOURS OF MAY 21.

DISTRIBUTION LIST FOR FINAL REPORT

Contract NAS3-7939

Address	Number of Copies
1. National Aeronautics and Space Administration	
Washington, D. C. 20546	
Attn: RNT/James Lazar	1
RNW/Preston T. Maxwell	1
2. NASA-Lewis Research Center	
21000 Brookpark Road	
Cleveland, Ohio 44135	
Attn: Spacecraft Technology Procurement Section (M.S. 54-2)	1
Attn: Technology Utilization Office (M.S. 3-19)	1
Attn: Technical Information Division (M.S. 5-5)	1
Attn: Library (M.S. 60-31)	2
Attn: Spacecraft Technology Division	
a. C. C. Conger (M.S. 54-1)	1
b. W. P. Blake (M.S. 54-3)	4
c. R. J. Rulis (M.S. 54-3)	1
d. B. L. Sater (M.S. 54-3)	4
Attn: Electric Propulsion Laboratory	
a. D. L. Lockwood (M.S. 302-1)	1
b. H. R. Kaufman (M.S. 301-1)	1
Attn: Report Control Office (M.S. 5-5)	1
Attn: Office of Reliability and Quality Assurance (M.S. 500-203)	1
Attn: Jesse Hall (M.S. 77-1)	1
Attn: C. S. Corcoran, Jr. (M.S. 500-201)	1
Attn: F. Gourash (M.S. 500-201)	1
3. NASA Scientific and Technical Information Facility	
P. O. Box 33	
College Park, Maryland 20740	
Attn: NASA Representative RQT-2448	6
4. NASA-Marshall Space Flight Center	
Huntsville, Alabama 35812	
Attn: Library	1
Attn: Robert Harwell	1
Attn: Joseph Parker	1
5. Westinghouse Electric Corporation	
Aerospace Electrical Division	
P. O. Box 989	
Lima, Ohio 45802	
Attn: Library	1
Attn: H. B. James	1

Address	Number of Copies
6. AFWL Kirtland AFB, New Mexico 87417 Attn: WLPC/Capt. C. F. Ellis	1
7. Aerospace Corporation P. O. Box 95085 Los Angeles, California 90045 Attn: Library/Technical Documents Group	1
8. Jet Propulsion Laboratory 4800 Oak Grove Drive Pasadena, California 91103 Attn: Library. Attn: Jack Sterns	1 1
9. Hughes Research Laboratories 3011 Malibu Canyon Road Malibu, California 90265 Attn: G. E. Brewer	1
10. Electro-Optical Systems, Inc. 300 North Balstead Pasadena, California 91107 Attn: John Davis	1
11, Westinghouse Electric Corporation P. O. Box 10596 Pittsburgh, Pennsylvania 15235 Attn: A. W. B, Walker	1
12. NASA Manned Spacecraft Center Houston, Texas 77001 Attn: Library	1
13. TRW, Inc. TRW Systems One Space Park Redondo Beach, California 90278 Attn: Dr. F. Kraus	1
14. Westinghouse Astronuclear Laboratories Electric Propulsion Laboratory Pittsburgh, Pennsylvania 15234 Attn: Library	1
15. TRW, Inc. New Product Research 23555 Euclid Avenue Cleveland, Ohio 44117 Attn: Paul H. Mc Gerroll	1

	Address	Number of Copies
16.	NASA Flight Research Center P. O. Box 273 Edwards, California 93423 Attn: Library	1
17.	NASA Goddard Space Flight Center Greenbelt, Maryland 20771 Attn: Library Attn: Robert L. Weitzel Attn: Fred C. Yagerhofer	1 1 1
18.	Hughes Aircraft Corporation Space Systems Division El Segundo, California Attn: W. J. Muldoon	1
19.	NASA Electronics Research Center 575 Technology Square Cambridge, Massachusetts 02039 Attn: Library Attn: Dr. Frederick Niemann	1 1
20.	Duke University Durham, North Carolina 27706 Attn: Dean, College of Engineering Attn: Dr. Thomas G. Wilson, Chairman E. E. Dept.	1 1
21.	U. S. Army Electronics Laboratory Power Conditioning Section Ft. Monmouth, New Jersey Attn: Frank Wrublowski	1
22.	NASA-Ames Research Center Moffett Field, California 94035 Attn: Library	1
23.	NASA-Langley Research Center Langley Field Station Hampton, Virginia 23365 Attn: Technical Library	1
24.	R. D. Blackburn 43-568 GE Co., 100 Woodlawn Ave. Pittsfield, Mass. 01201	1